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Title: R&D for Superconducting RF Structures at Los Alamos

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Intended for: Seminar at Cornell University on 22 Feb. 2013

R&D for Superconducting RF Structures at Los Alamos

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Mechanical Design & Engineering Group

Accelerator Operations & Technology Division

Seminar at Cornell University, 22 February 2013

LA-UR-13-21205

Outline

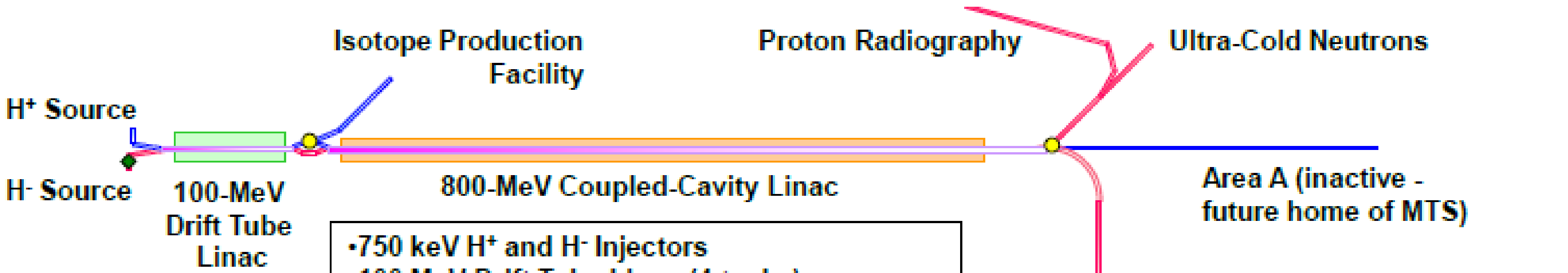
- Introduction
- Studies on MgB_2
- Seamless cavity fabrication (collaboration with KEK)
- New Nb films on copper (collaboration with AASC)
- Photonic band gap (PBG) structure (collaboration with Niowave)

Los Alamos Neutron Science Center (LANSCE)

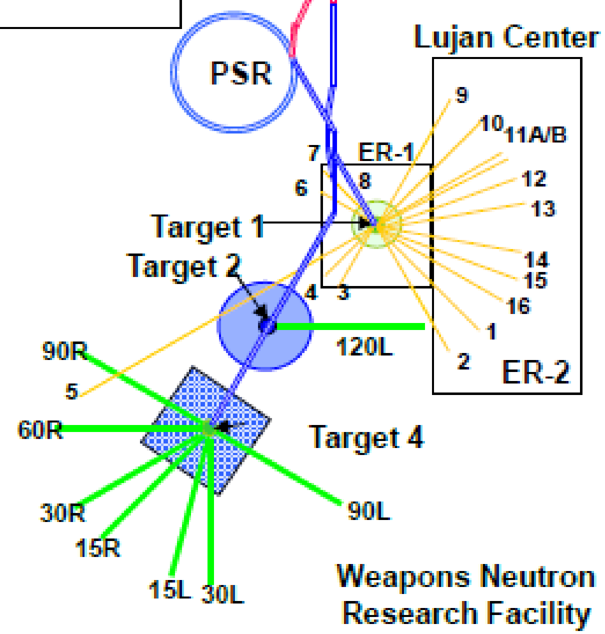
800-MeV (~1 MW) *LANSCE (formerly LAMPF) linac is the heart of the facility -first beam in 1972.*

View from west

H+ and H- beams are delivered to experimental facilities simultaneously



- 750 keV H⁺ and H⁻ Injectors
- 100 MeV Drift Tube Linac (4 tanks)
- 800 MeV Coupled Cavity Linac (44 modules)
- 800 MeV Compressor Ring (PSR)



Area	Typical Repetition Rate [Hz]	Typical Pulse Length [μs]	Linac Beam Species	Typical Chopping Pattern	Average Beam Current [μA]	Nominal Energy [MeV]	Avg Beam Power [kW]
Lujan	20 sole use	625	H-	290 ns/358 ns	100 -125	800	80 - 100
WNR Tgt4	≤40	625	H-	1 μpulse every ~1.8 μs	≤ 2	800	< 1.6
UCN	20	625	H-	Lujan-beam like to unchopped	< 5	800	< 4
pRad	~1	625	H-	60 ns bursts every ~1 μs	< 1	≤800	< 1
IPF	≤30 in Pulsed mode	625	H+	NA	≤ 250	100	≤ 25
AreaA inactive	≤100	625	H+	NA	1000	800	~ 800

○ kicker
◆ chopper

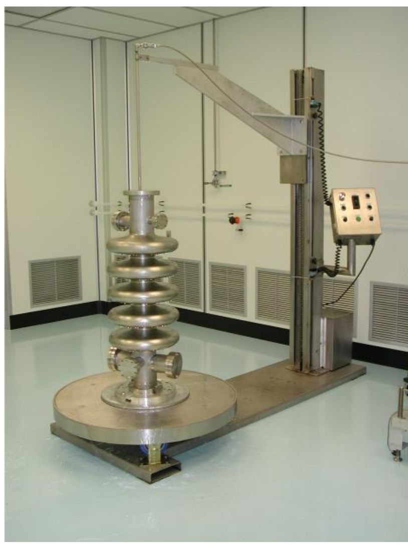
View from east

SRF Lab facilities

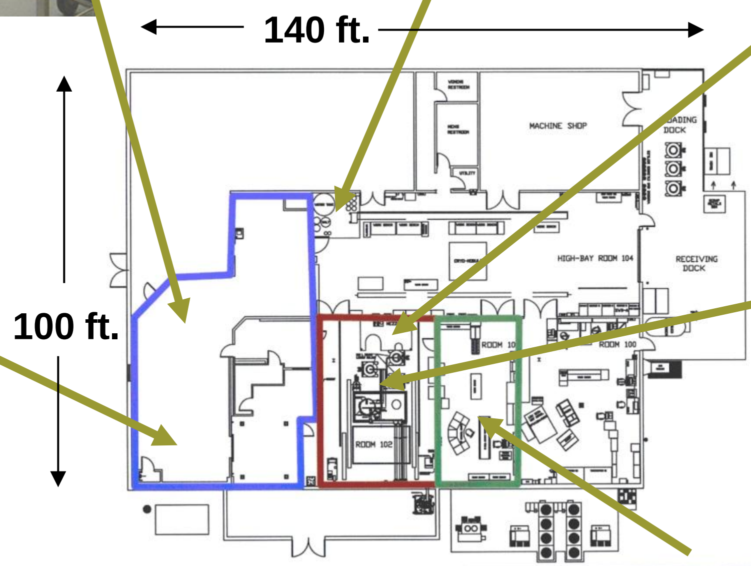
2600 ft^2 Clean Room

Ultra-Pure Water Supply 2000 G/day with 1500 G Tank

Two 38” Diameter Inserts + a 17” insert



High-Pressure Rinse Equipment



Building MPF-17

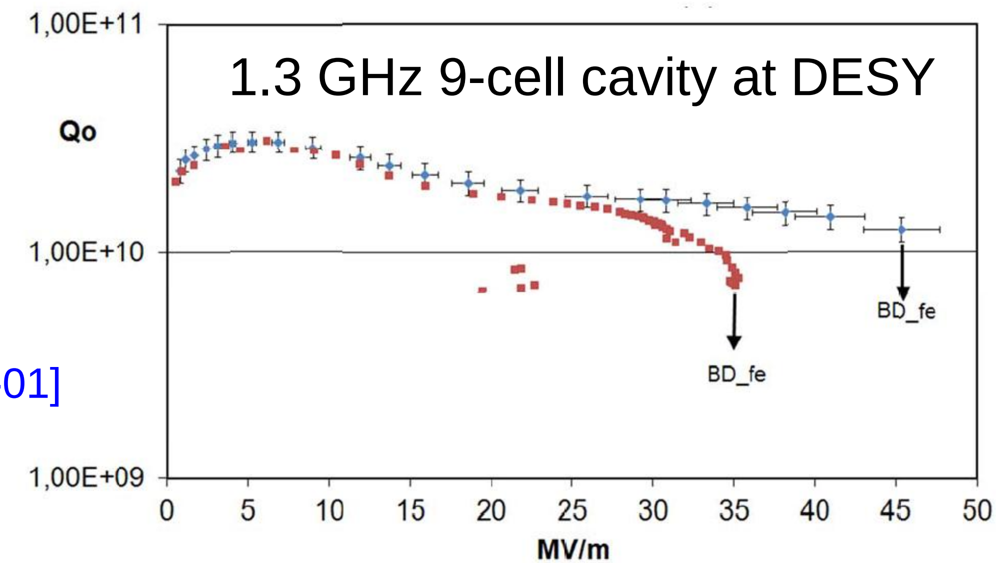
38” + 17” Diameter, 10 ft Deep Cryostats and Moveable Shield

Control, Tuning Room

BCP, coating and materials science facilities are at different sites in LANL.

Current R&D is focused on new materials and new fabrication techniques that will enhance performance and reduce cost of future SRF structures

- **Recent SRF cavities (especially 1.3 GHz elliptical cells) made of bulk Nb are approaching its theoretical limit of E_{acc} ~ 50 MV/m (B_{peak} ~ 200 mT).**
- **While it is important to increase the production reliability and yield of high-quality Nb SRF cavities, finding a new material that could overcome the limit of Nb technology is becoming increasingly important for SRF technology to be more attractive and open up other opportunities.**

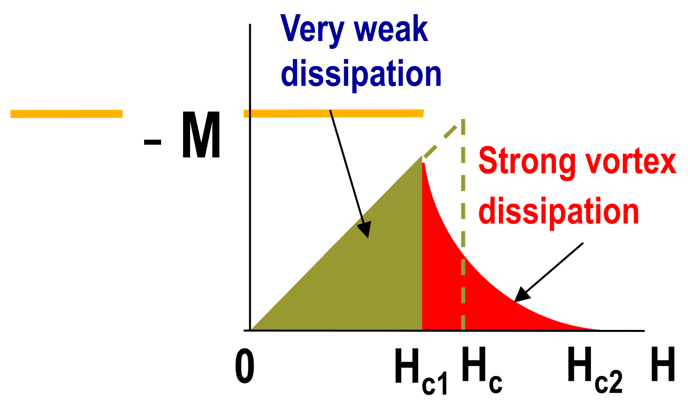


[Aderhold et al., TTC-Report-2011-01]

Figure 2: First and final $Q_0(E_{acc})$ performance of nine-cell cavity AC155 at 2 K after EP treatment. Notice the Q-switches at around 30 MV/m down to 18 MV/m – 24 MV/m at Q_0 below 10^{10}

Studies on MgB_2

Type II superconductor



- Very weak dissipation
- at $H < H_{c1}$ ($Q = 10^{10}$-10^{11})
- Q drop due to vortex
- dissipation at $H > H_{c1}$

Nb has the highest lower critical field H_{c1}

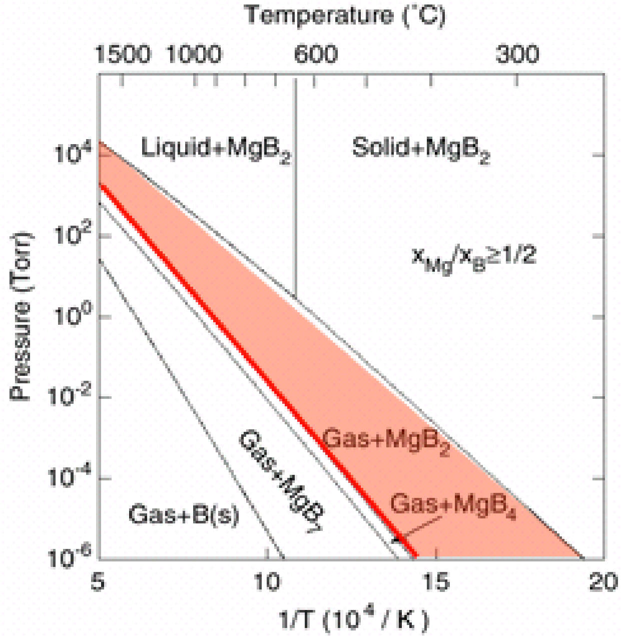
$$H_{c1} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right)$$

- **Thermodynamic critical field H_c (surface barrier for vortices disappears)**

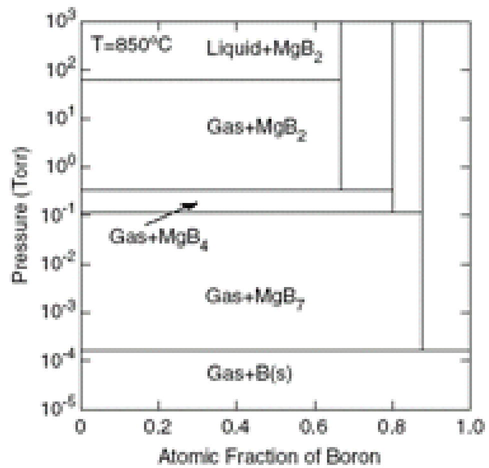
$$H_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}$$

Material	T_c (K)	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	$\lambda(0)$ [nm]
Pb	7.2	0.08	na	na	48
Nb	9.2	0.2	0.17	0.4	40
Nb_3Sn	18	0.54	0.05	30	85
NbN	16.2	0.23	0.02	15	200
MgB_2	40	>0.43	>0.03	3.5	140
YBCO	93	1.4	0.01	100	150

Keys to Growth of MgB_2 Films



Liu *et al.*, APL 78, 3678 (2001)



— **Keep a high Mg pressure for phase stability**
For example, at 600° C Mg vapor pressure of 0.9 mTorr or Mg flux of 500 Å/s is needed

— **No need for composition control**, as long as the Mg:B ratio is above 1:2.

— **Keep oxygen away**: Mg reacts strongly with **oxygen** - forms MgO, reduces Mg vapor pressure.

— **Avoid carbon**: **Carbon** doping reduces T_c and increases resistivity

[Xi, Thin film workshop, JLAB, 18-20 July 2012]

Very smooth films prepared with reactive co-evaporation at STI [Moeckly and Ruby, SUST 19 (2006) L21]

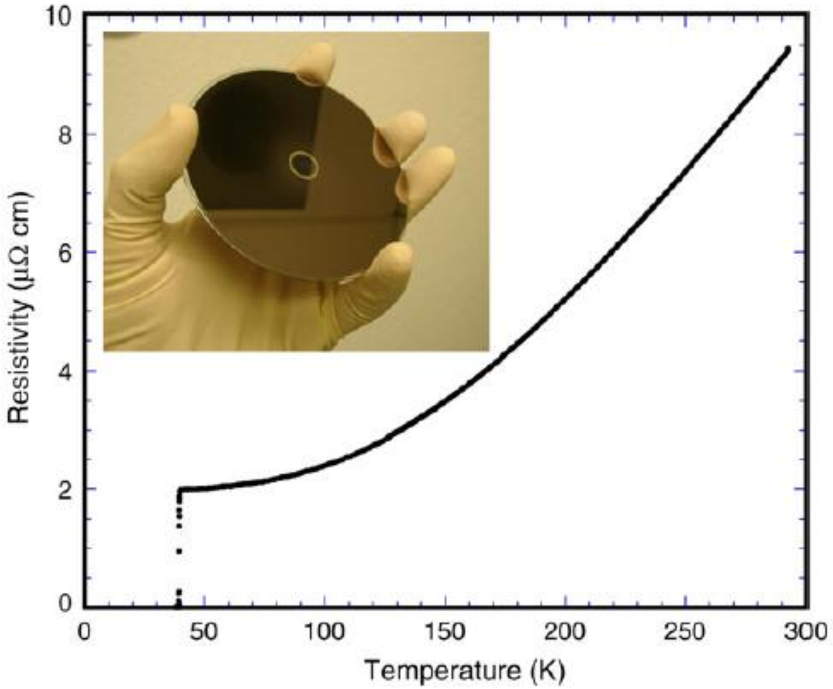
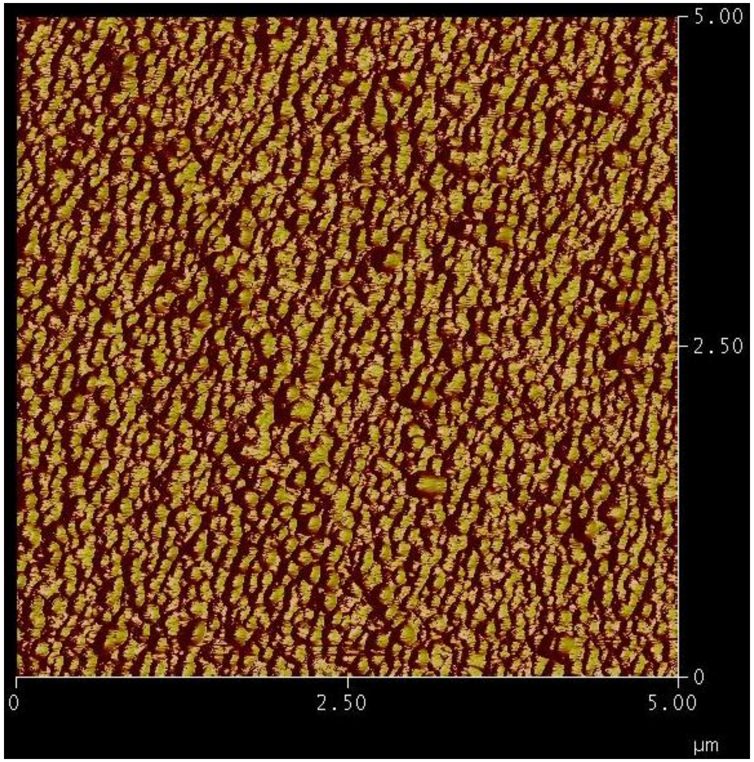


Figure 2. Resistivity versus temperature for an MgB_2 film deposited on polycrystalline alumina. This film was grown at 550 °C to a thickness of 550 nm and has a zero-resistance T_c value of 39.1 K. The inset shows a photograph of an MgB_2 film grown on a 4 inch diameter r-plane sapphire substrate.

500-nm MgB_2 film on Nb
RMS surface roughness = 3.0 nm



[D. Oates, SRF Thin Film Workshop 2012]

In 2005, we showed that R_s can be lower than that of Nb and there is little increase in R_s with fields up to 120 Oe limited by available power [Tajima et al. PAC2005]

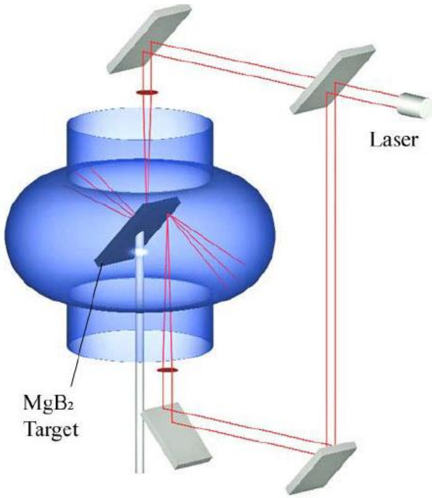


Figure 7: An idea for coating a cavity using a MgB_2 target and a KrF excimer laser.

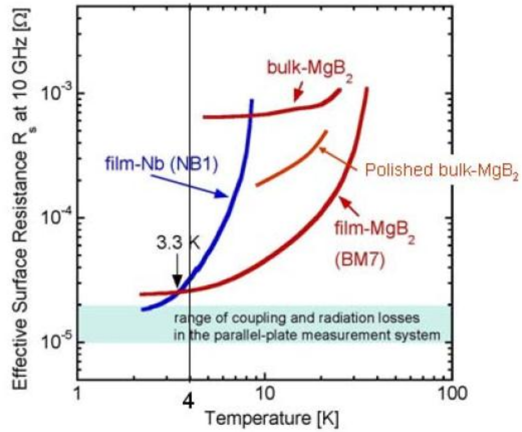


Figure 3: Surface resistance vs. temperature of a 400 nm MgB_2 film coated on a sapphire substrate. Bulk samples and Nb data are shown for comparison. [6]

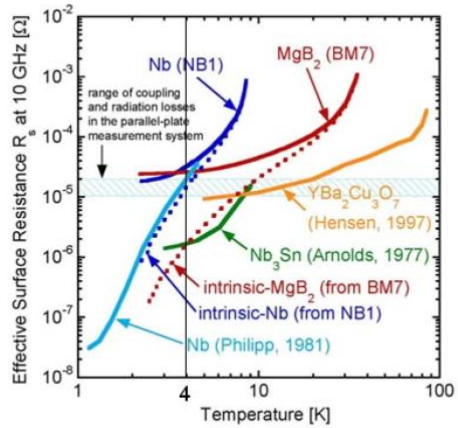


Figure 4: Prediction of intrinsic (BCS) surface resistance (dotted line) from experimental data. [6]

Deposited with reactive co-evaporation at Superconductor Technologies, Inc. (STI)

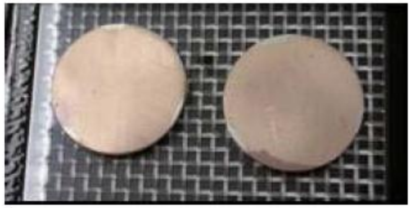


Figure 5: MgB_2 coated Nb disks of 14.6 mm in diameter.

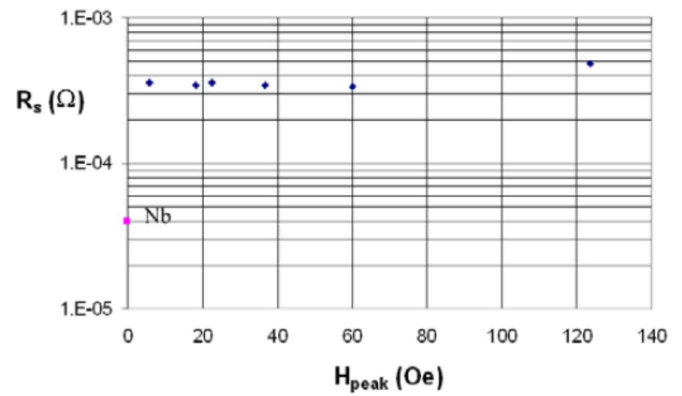


Figure 6: R_s of the Nb TE_{011} mode cavity with a MgB_2 sample at the center of the bottom plate, as a function of the peak magnetic field on the sample. The data was converted to 10 GHz using an f^2 law.

Collaboration with Romanenko at Cornell

In 2005-2006, we proposed to coat cavity with pulsed laser deposition (PLD), but the PLD films had poor quality [Tajima et al. EPAC2006]

$T_c \sim 27$ K

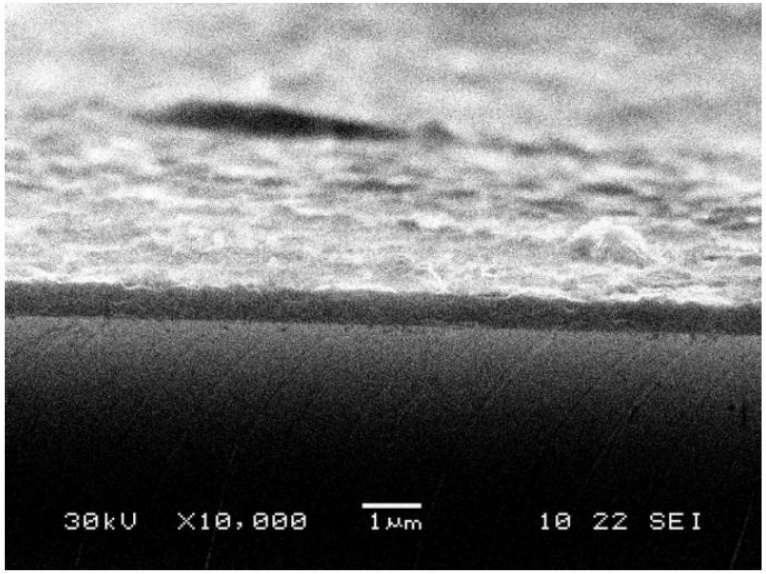


Figure 3: A SEM image of the cross section of off-axis PLD MgB_2 film (ID: 300705v) on Al_2O_3-C substrate. The film thickness is 500-700nm.

Tested by Romanenko at Cornell

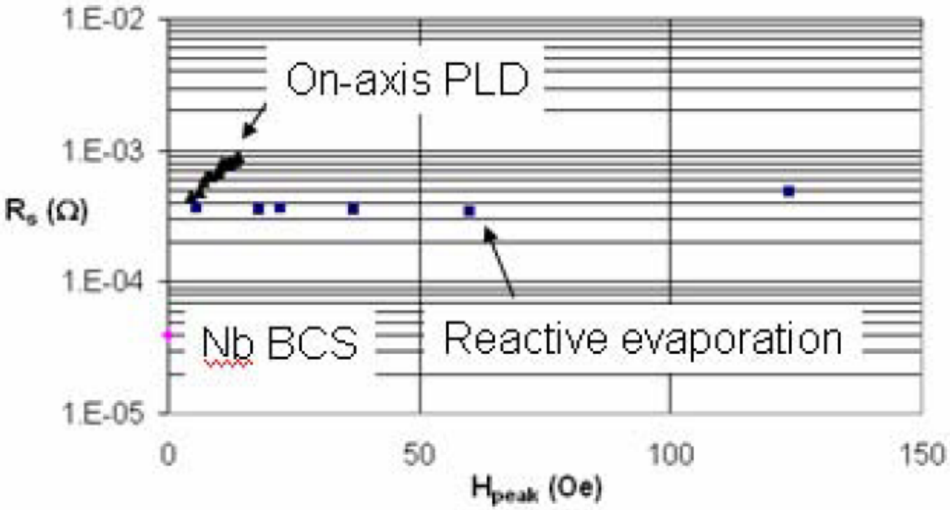


Figure 6: Surface resistance at 10 GHz as a function of surface magnetic field. The data was scaled from 6 GHz data using f^2 law.

Collaboration with Yue Zhao of U. Wollongong, Australia

Summary of MgB_2 deposition techniques that we have tested

Reactive Co-evaporation by Brian Moeckly et al., at STI

Substrate
T ~ 550 °C

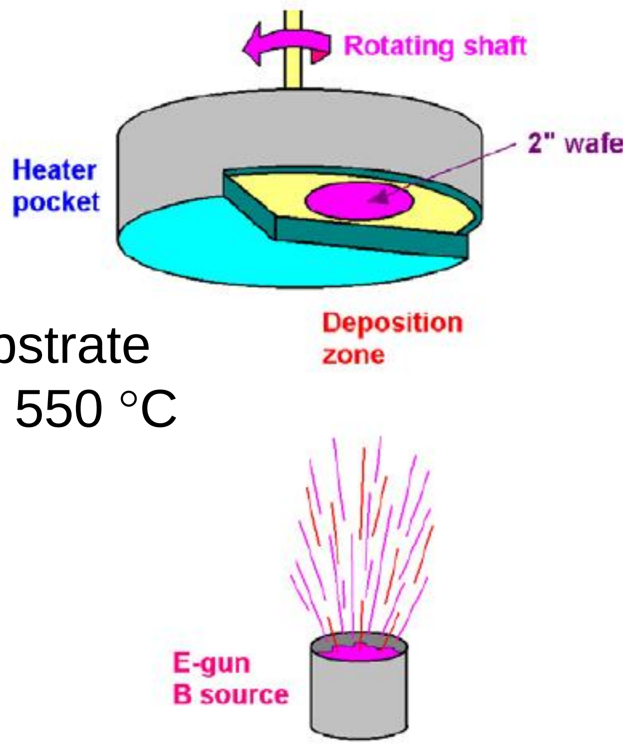


Figure 1: MgB_2 coating system at STI. [5]

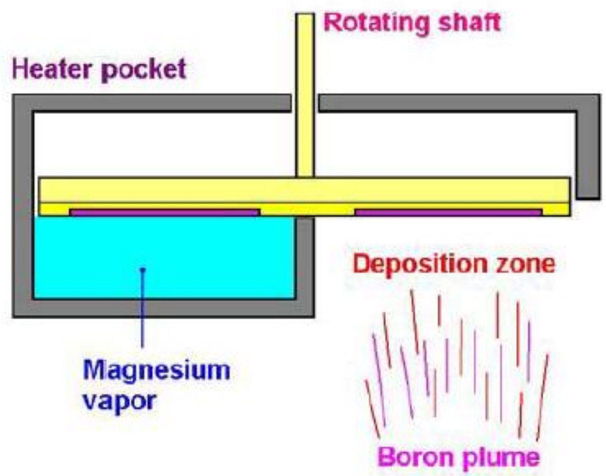


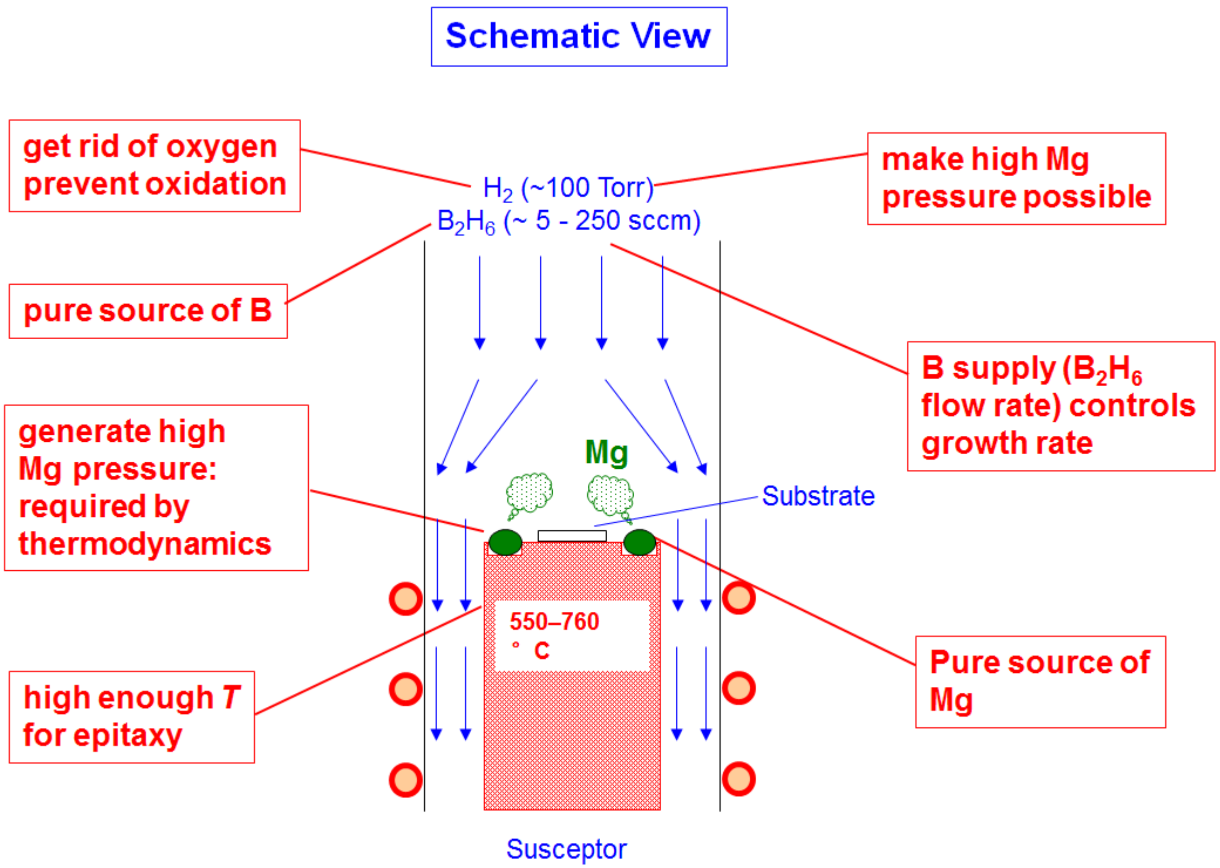
Figure 2: Cross section of the deposition chamber. [5]

T_C ~ 39 K

[Moeckly et al., ASC2004]
[Tajima et al., PAC2005]

Summary of MgB_2 deposition techniques that we have tested (cont.)

Hybrid Physical-Chemical Vapor Deposition

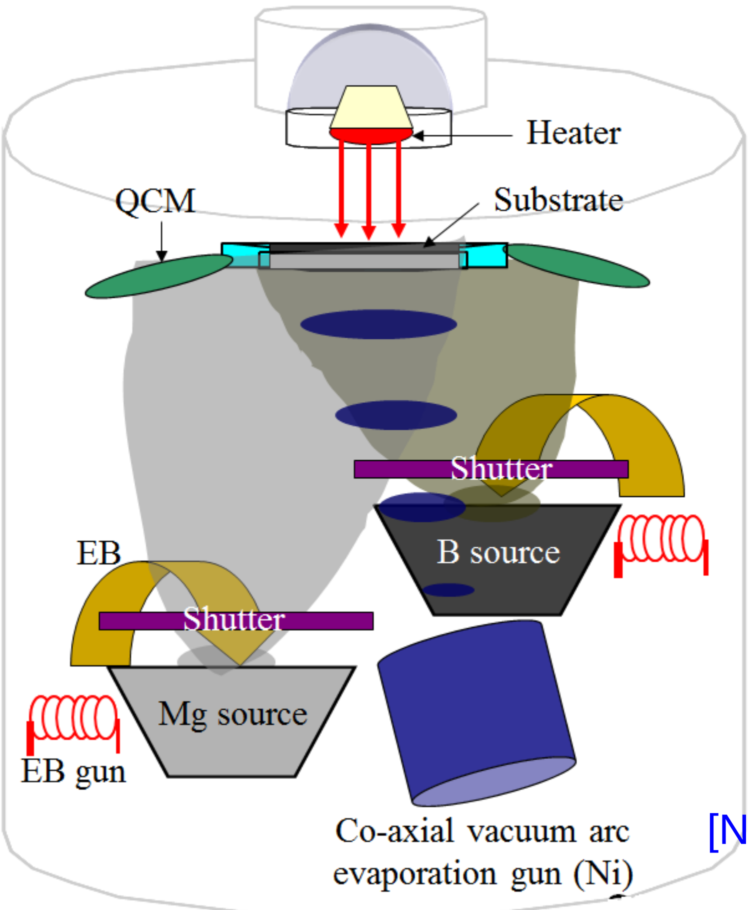


T_c ~ 40 K

[Xi, Thin film workshop, JLAB, 18-20 July 2012]

Summary of MgB_2 deposition techniques that we have tested (cont.)

E-beam co-evaporation by Toshiya Doi et al. of Kagoshima U., Japan



Requires base pressure <~1 x 10^{-9} Torr to avoid effect of oxygen

T_c ~ 32 K

Substrate T ~ 250 °C

[Nagatomo et al., Physica C 426 (2005) 1459]

Summary of MgB_2 deposition techniques that we have tested (cont.)

Off-axis Pulsed Laser Deposition (PLD) by Y. Zhao of U. Wollongong, Australia

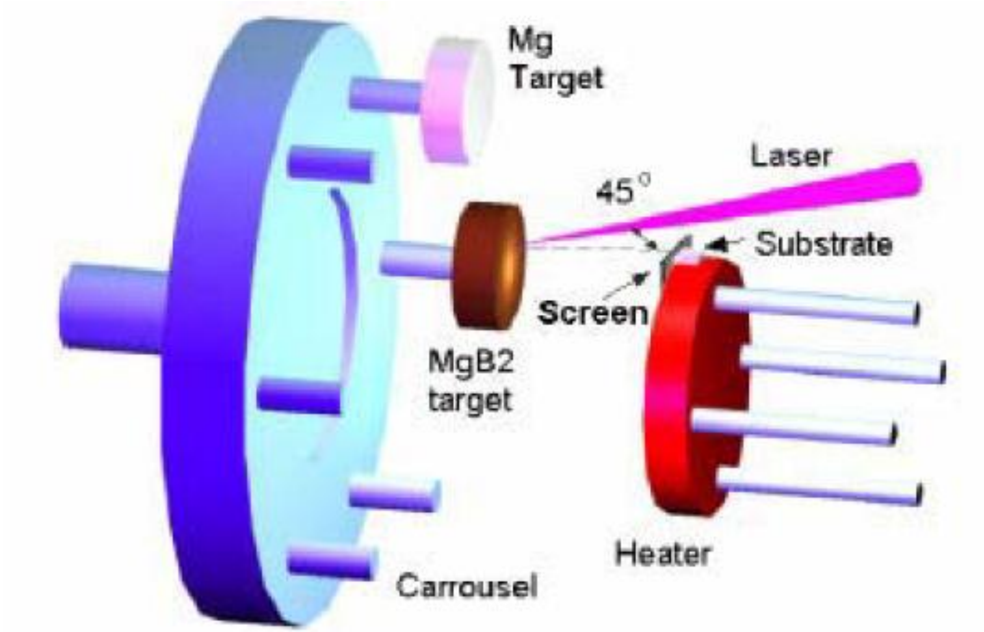


Figure 1: An illustration of off-axis PLD [1].

A KrF laser (λ=248 nm, 25 ns) was used in 120 mTorr Ar atmosphere, then an *in-situ* annealing was carried out at 680 °C for 2 min in a 760 Torr Ar atmosphere [7].

T_c ~ 27 K

Substrate
T ~ 680 °C

In 2007, we started high-power RF tests with 2-inch diameter disks in collaboration with SLAC using 11.4 GHz RF short pulse (~ 1 μs) and a TE_{013}-mode cavity

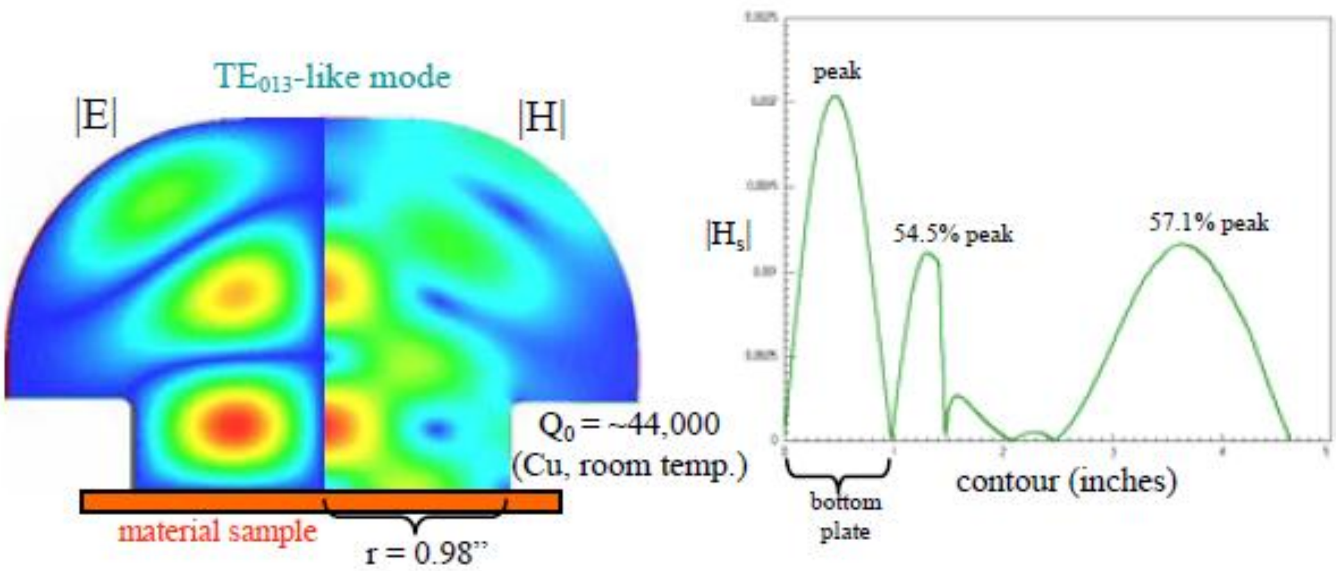


Figure 2: Electric and magnetic fields in the "mushroom" cavity (left) and magnetic field profile along the surface of the cavity (right).

[Tantawi et al. PAC2007]

Due to the low Q of the host cavity made of copper, R_s did not have enough sensitivity. Also, thermal effect seems to have been involved despite a short pulse is used.

STI film deposited at 550 °C on top of ALD alumina

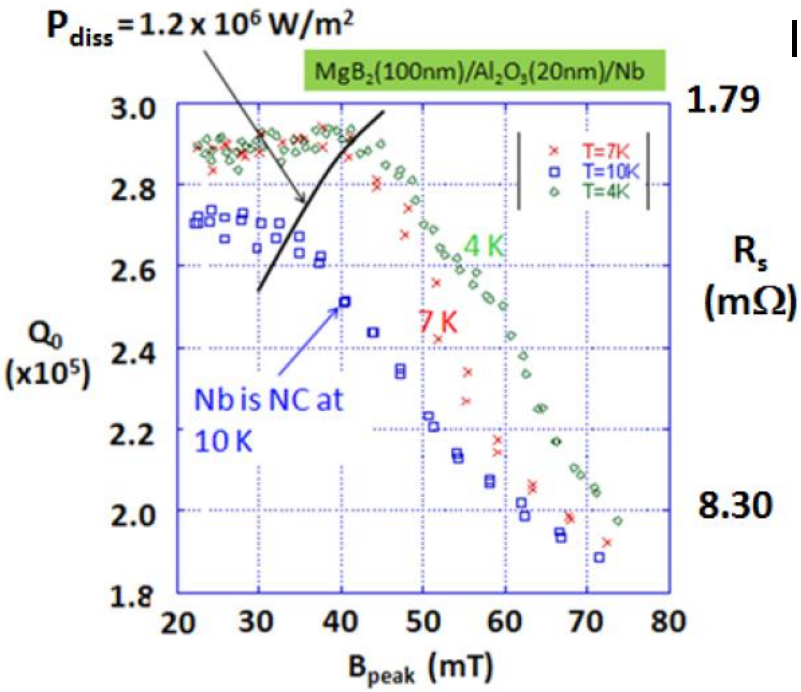


Figure 11: Q_0 as a function of B_{peak} at 4 K, 7 K and 10 K for the MgB_2(100 nm)/Al_2O_3(20 nm)/Nb sample shown in Fig. 8. The solid line is a curve described by Eq. (2) with $P_{diss} = 1.2 \times 10^6$ W/m^2.

Inter-diffusion layer causes high RF loss

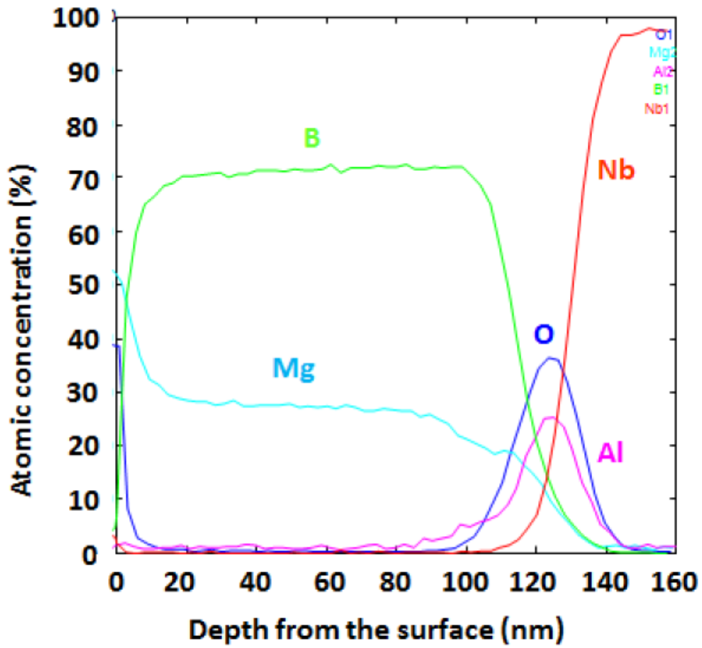


Figure 12: Auger depth profile of the MgB_2(100 nm)/Al_2O_3(20 nm)/Nb sample shown in Fig. 8. Inter-diffusion of coating components at the interfaces is observed.

[Tajima et al., SRF2011]

In 2010, we started using magnetization measurements to evaluate vortex penetration field B_{vp} to determine the fundamental limit of MgB_2 thin films

~290 nm T_c ~ 31.8 K

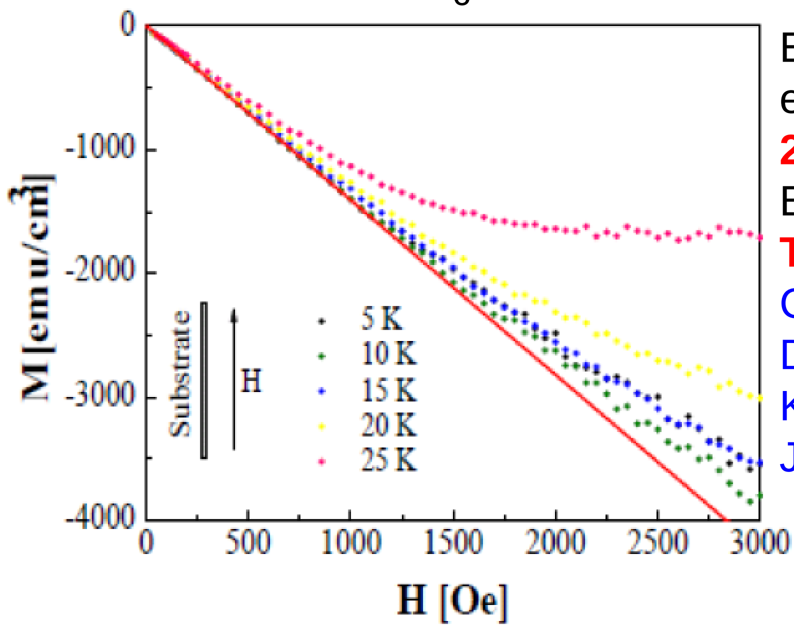


Figure 4: Magnetization curves as a function of applied magnetic field at various temperatures for ~290 nm thick MgB_2 film (T_c ~ 31.8 K) deposited on a Si substrate at Kagoshima Univ.

E-beam co-evaporation at **250 °C**

Base p ~ **1 x 10^{-9} Torr**

Collaboration with Doi et al. of Kagoshima U., Japan

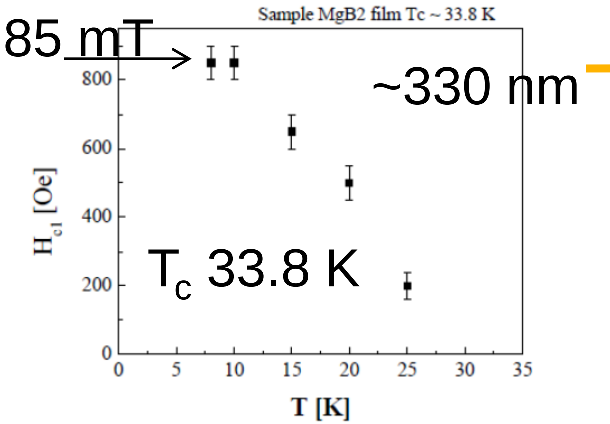


Figure 7: H_{c1} vs. sample temperature from magnetization measurements of ~330 nm thick MgB_2 sample prepared by Kagoshima Univ.

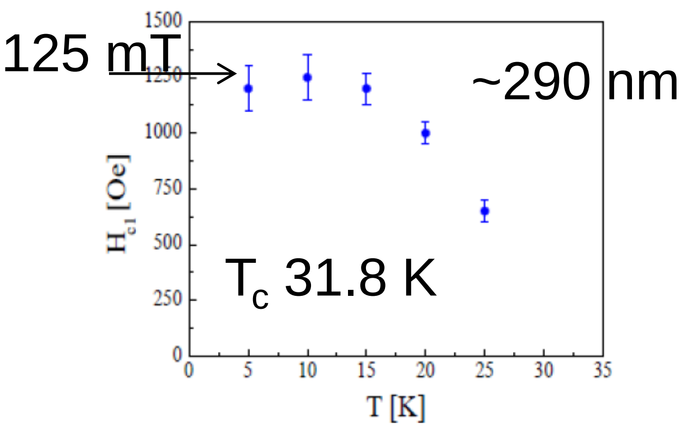


Figure 8: H_{c1} vs. sample temperature from magnetization measurements of ~290 nm thick MgB_2 sample (T_c ~ 31.8 K) prepared by Kagoshima Univ.

[Tajima, Haberkorn, Civale et al. LINAC2010]

We are looking at only this part

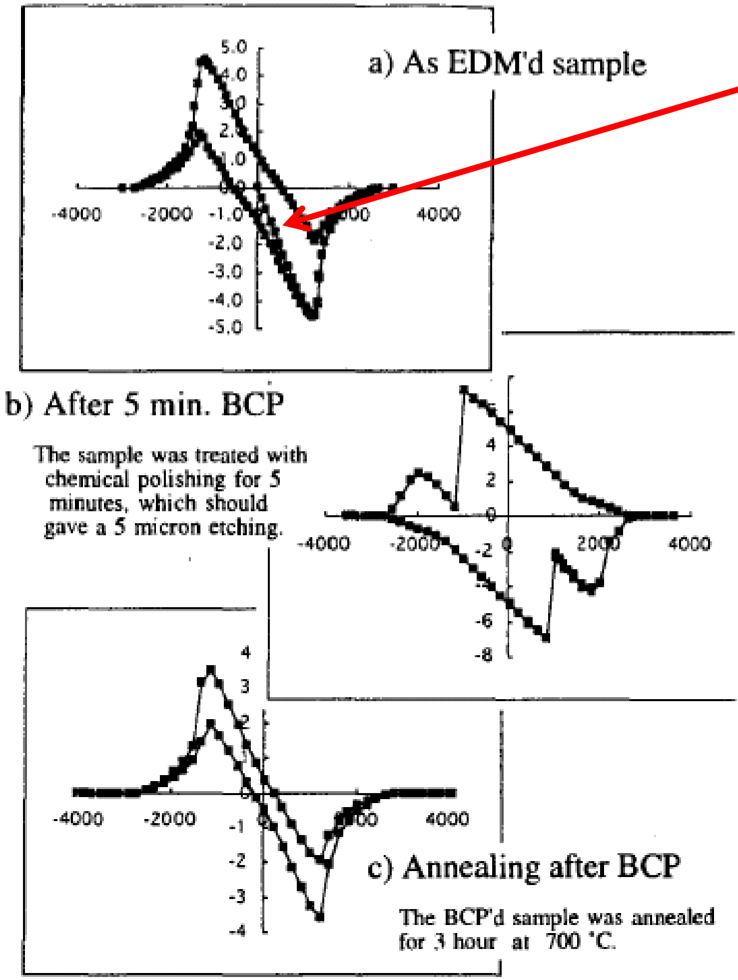


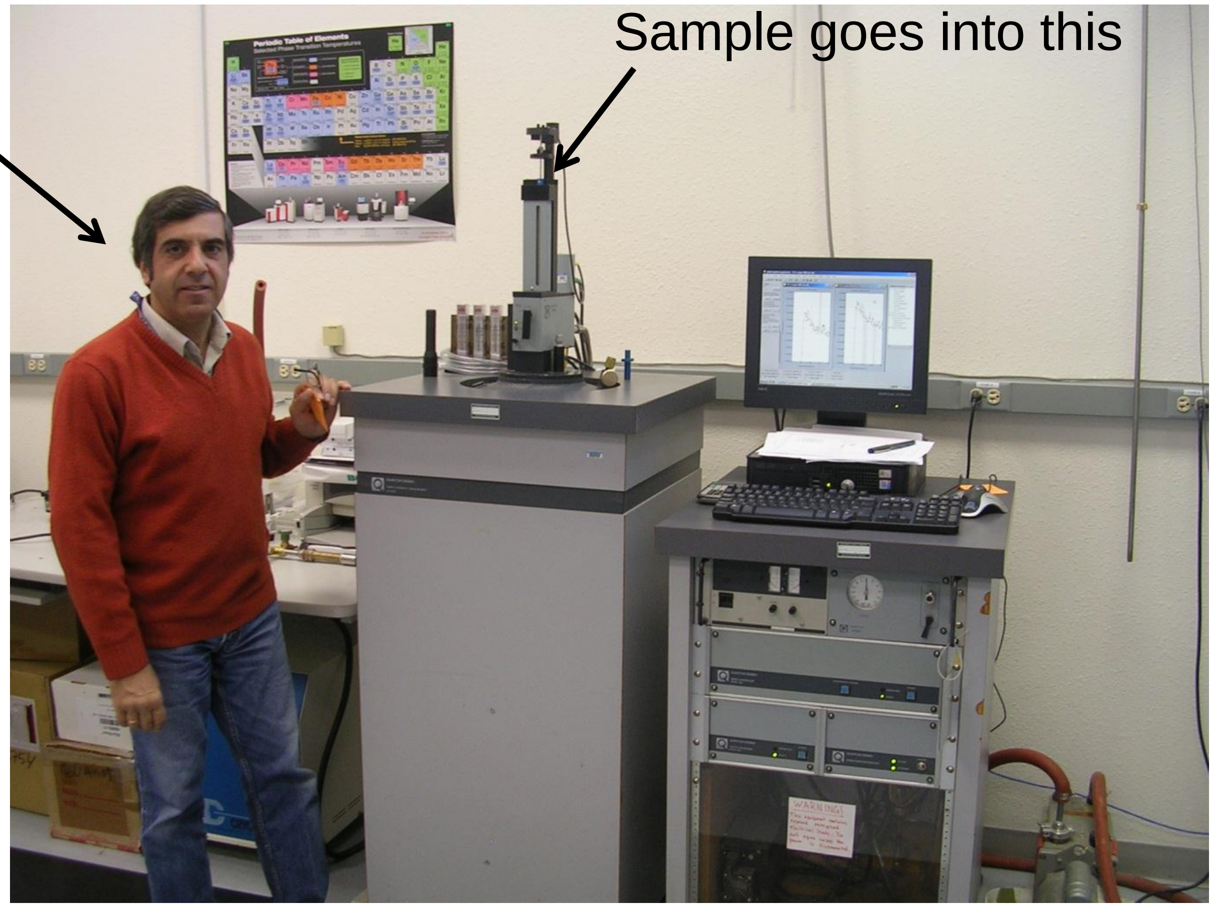
Fig. 2. Hysteresis appeared in magnetization curves. a) as EDM'd sample, b) after chemically polished the EDM'd sample, c) annealed after the CP'd sample.

Magnetization measurements were used for SRF cavity research in 1995 by Saito and Wake of KEK to evaluate the effect of surface treatments by looking at hysteresis curves.
The larger hysteresis means more imperfections and/or dislocations since vortices get pinned by them.

[Saito, Wake, SRF1995]

Recent studies focused on B_{vp} measurements using a Quantum Design SQUID magnetometer since it seems to be a reliable method to determine fundamental limit

At LANL,
Leonardo Civale
and his postdocs
have been
carrying out these
measurements

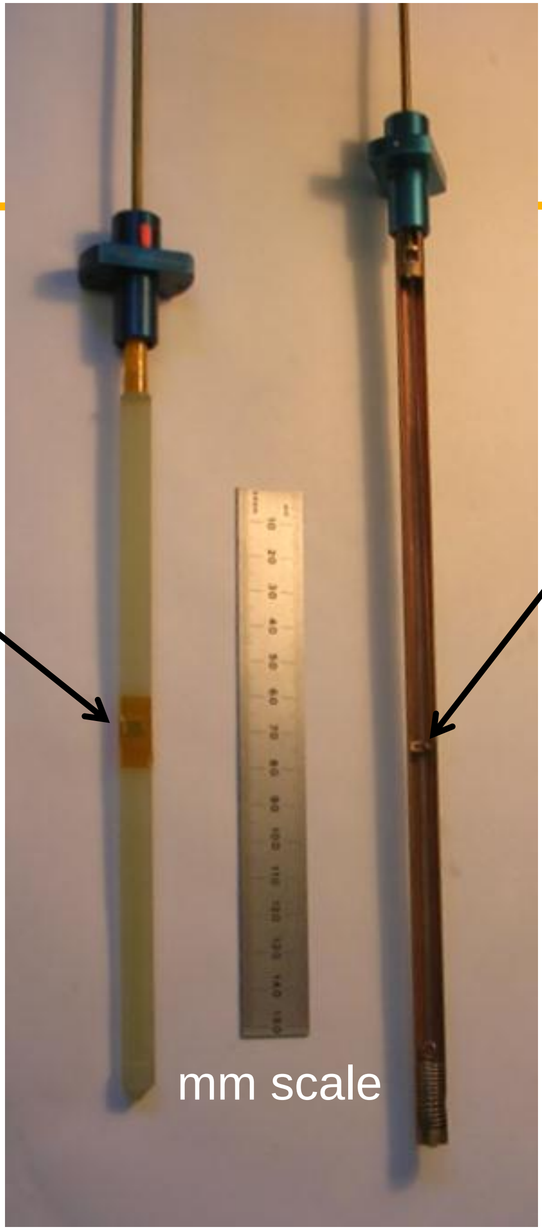


Samples

Typically ~5 mm x ~5 mm for coated films

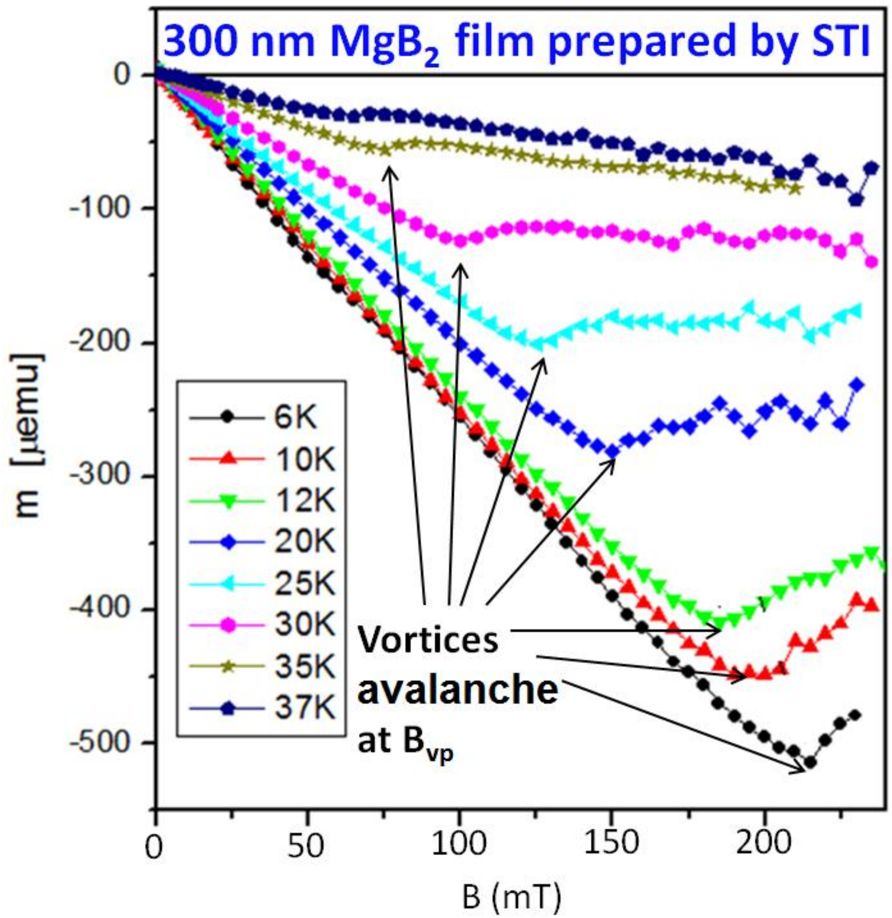
Nb reference was a rod with 2 mm diameter and 10 mm long cut out from a single grain RRR>300 Nb sheet

Rod or ellipsoid is better due to less edge effect, but difficult to uniformly coat



This sample holder has an angle adjustment mechanism

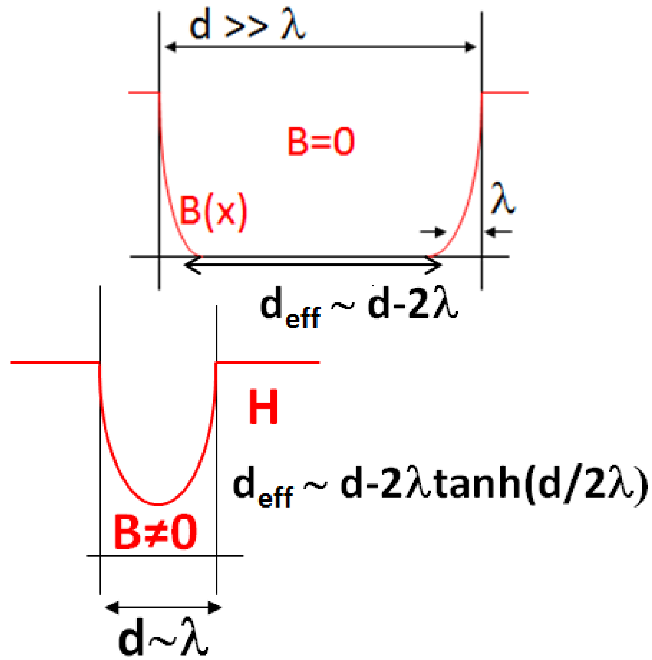
Meissner slope is proportional to the effective volume of the film, making it difficult to measure ultra-thin films due to small signal. Our present limit is ~200 nm



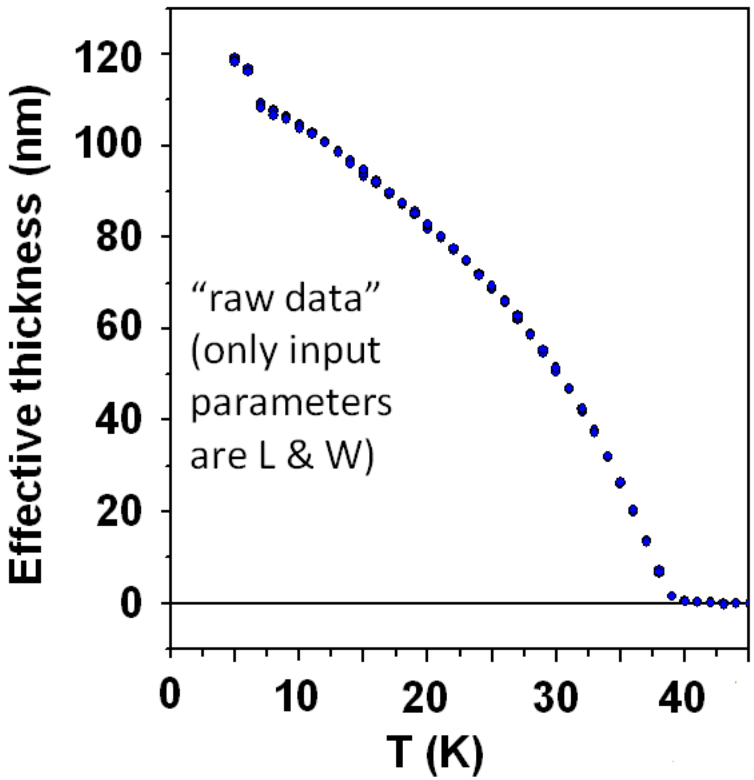
Meissner state:

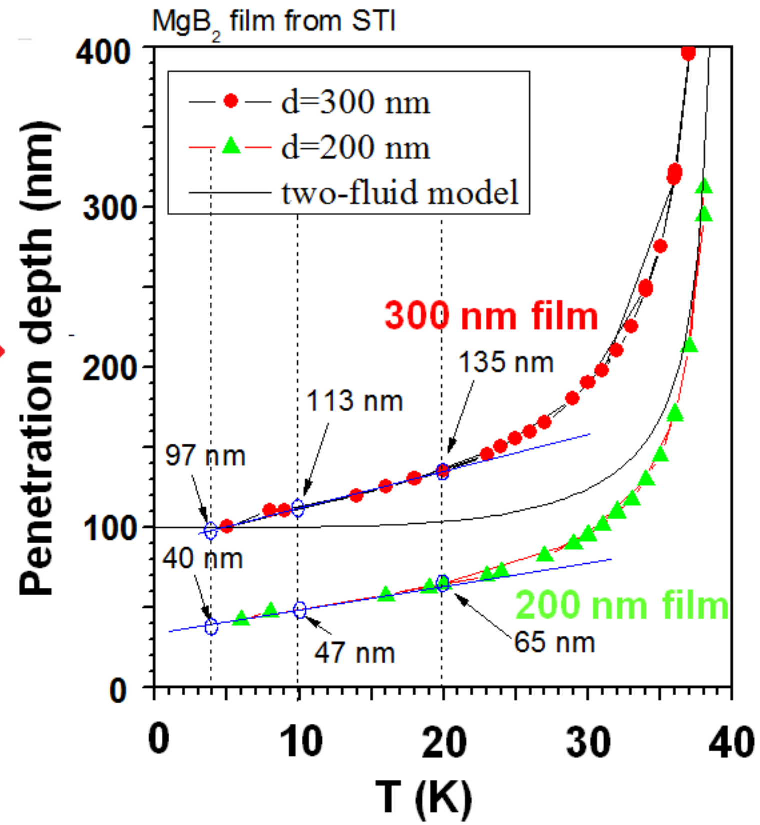
$dm/dH = -V_{eff}/4\pi \propto d_{eff}$

Slope changes with T due to the change in λ

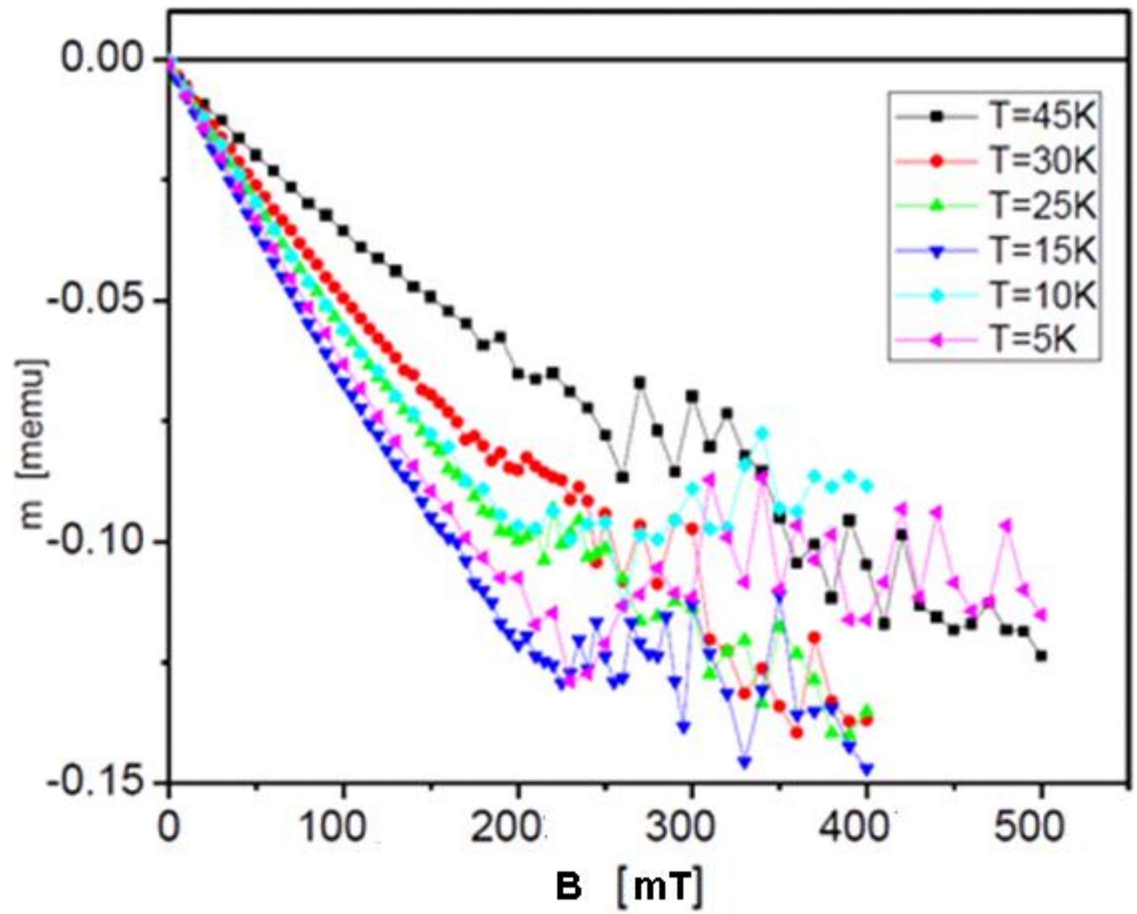


Penetration depth can be estimated from effective thickness. Penetration depth increases with higher temperature. This causes the reduction of effective thickness.

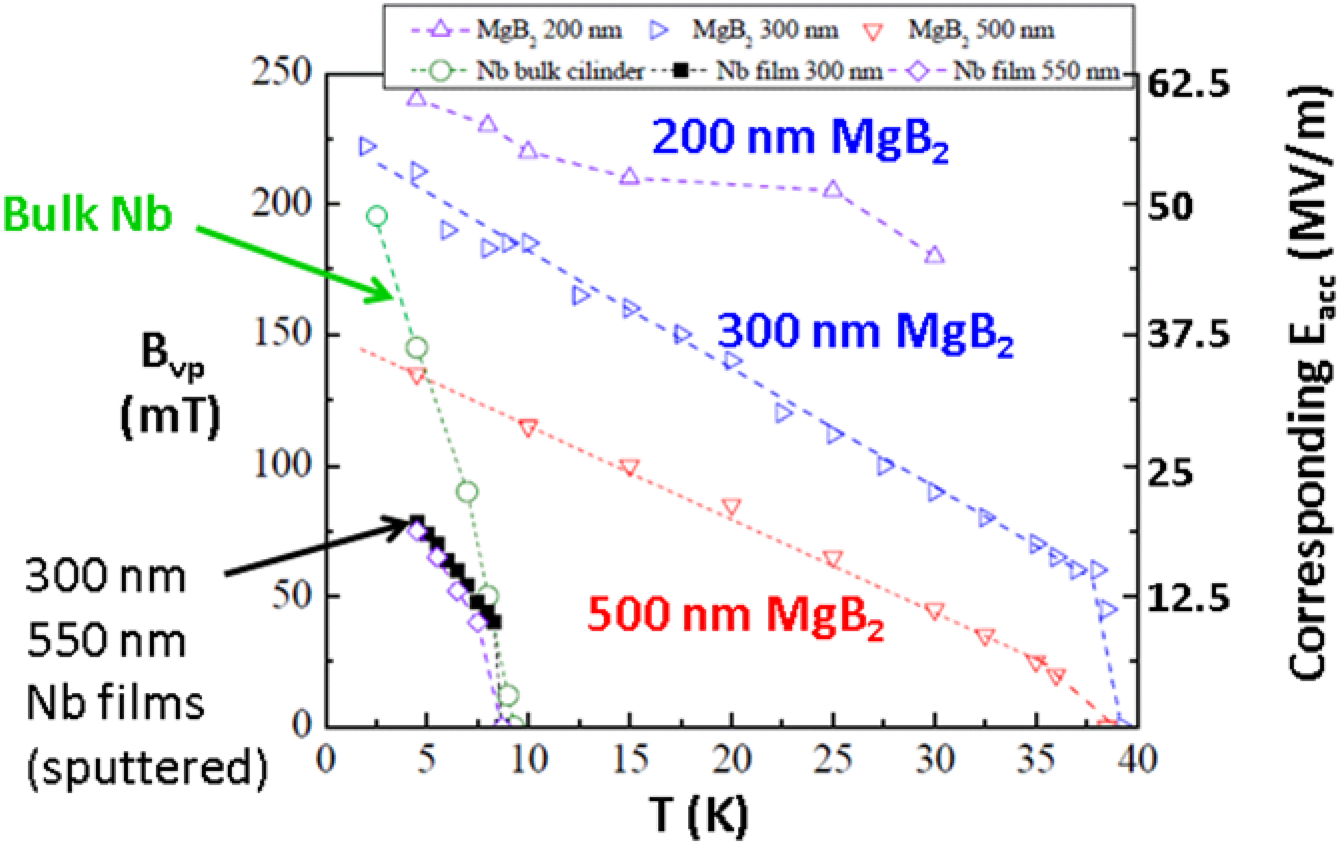




With a 200 nm sample, the signal got quite noisy at high fields, but was still measurable.



Summary of B_{vp} for STI films (200, 300 and 500 nm) compared with cavity-grade bulk Nb and sputtered Nb film. MgB$_2$ thin films show remarkably high B_{vp} !!

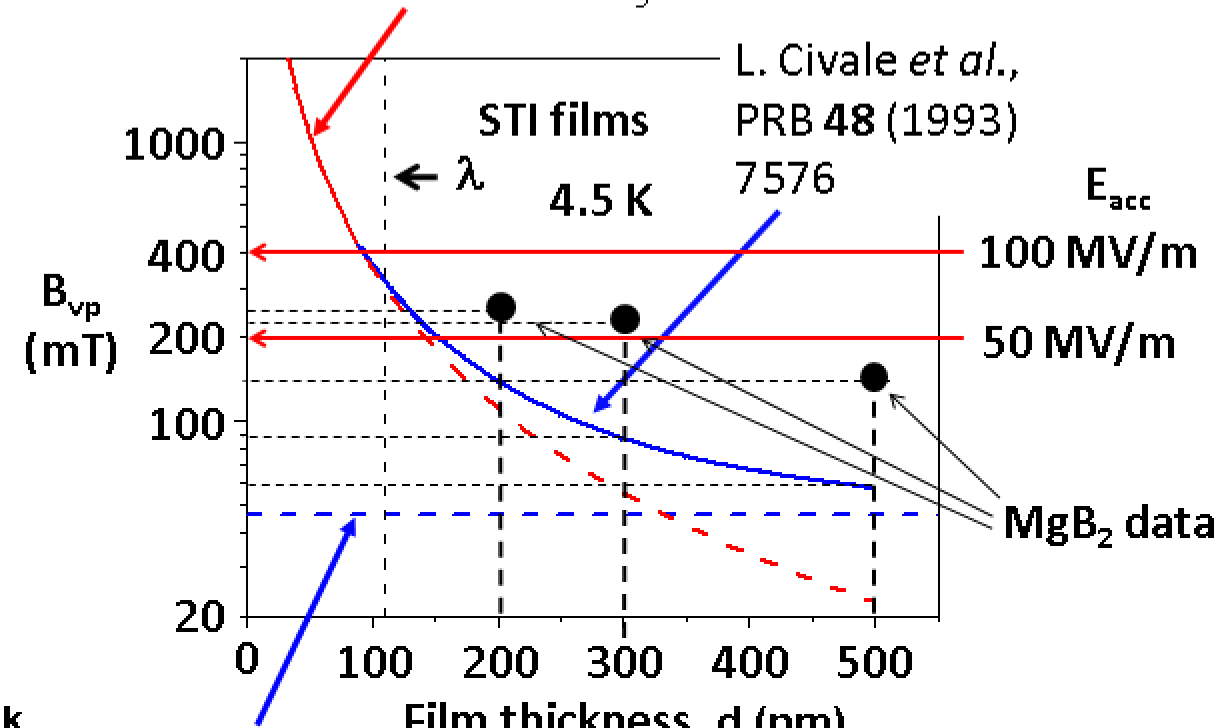


Assume B_{peak}/E_{acc} = 4 mT/(MV/m)

[Tajima et al. SRF2011] modified

Comparison with theoretical curve of B_{c1} for thin films assuming λ = 110 nm and ξ = 6 nm. Important finding here was that even the films with d>λ have high B_{vp}

$$B_{c1}\,(d \ll \lambda) \approx \frac{2\Phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}}$$ Gurevich, APL **88** (2006) 012511

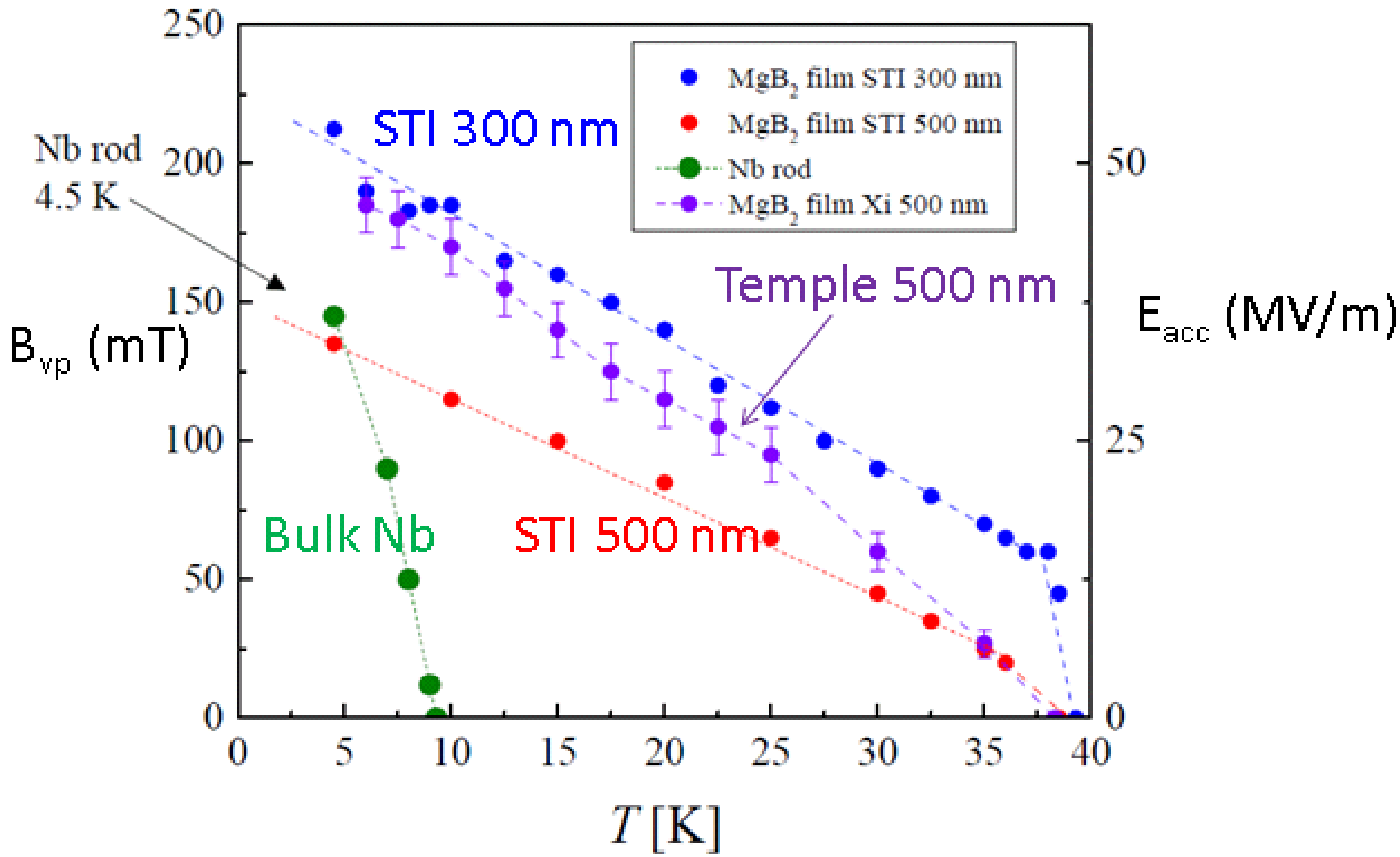


Bulk

$$B_{c1}\,(d \gg \lambda) = \frac{\Phi_0}{4\pi\lambda^2} \ln \kappa \sim 46 \text{ mT}$$

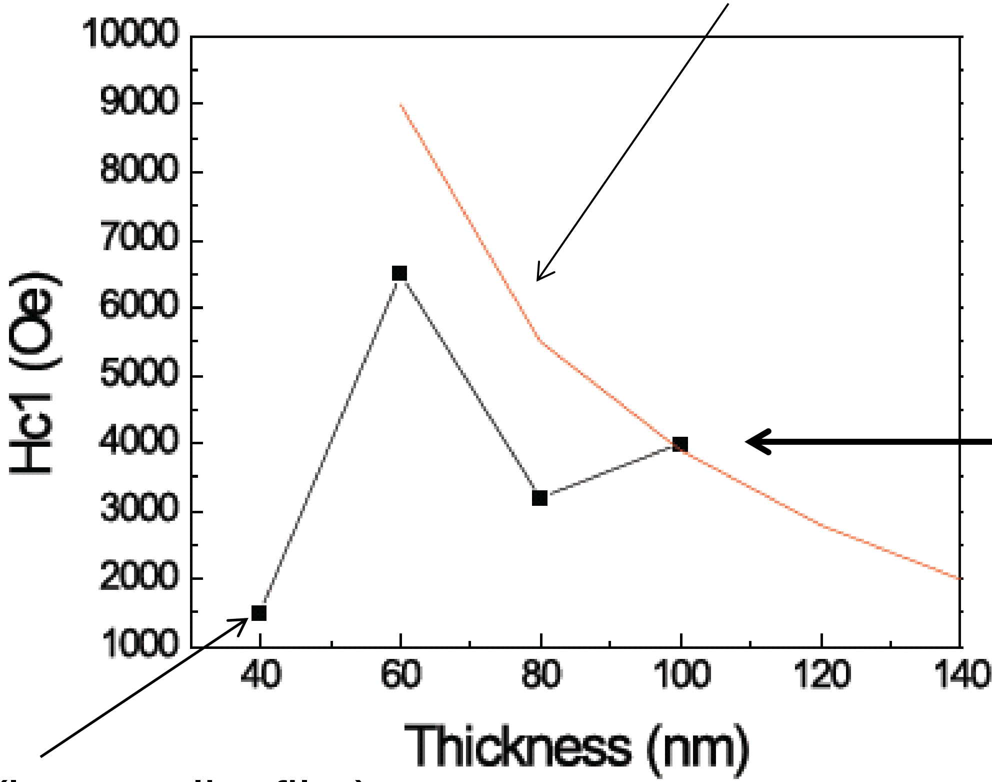
[Tajima et al. SRF2011] modified

Temple University (Xiaoxing Xi's group) samples prepared with hybrid physical chemical vapor deposition (HPCVD) also showed high B_{vp}



Recent results of thinner films prepared by Temple U. and measured by Beringer of the College of William and Mary showed $B_{c1} \geq 400$ mT ($H_{c1} \geq 4000$ Oe) with ≤100 nm films

Prediction assuming λ = 140 nm, ξ = 5 nm

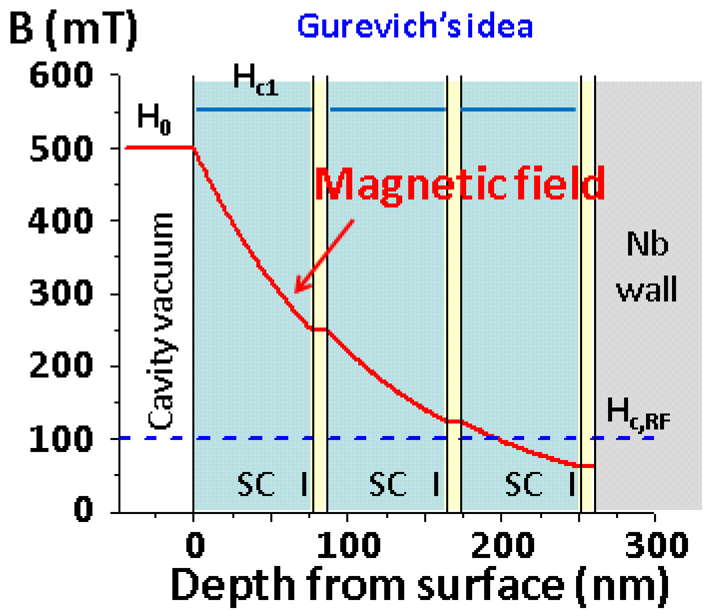


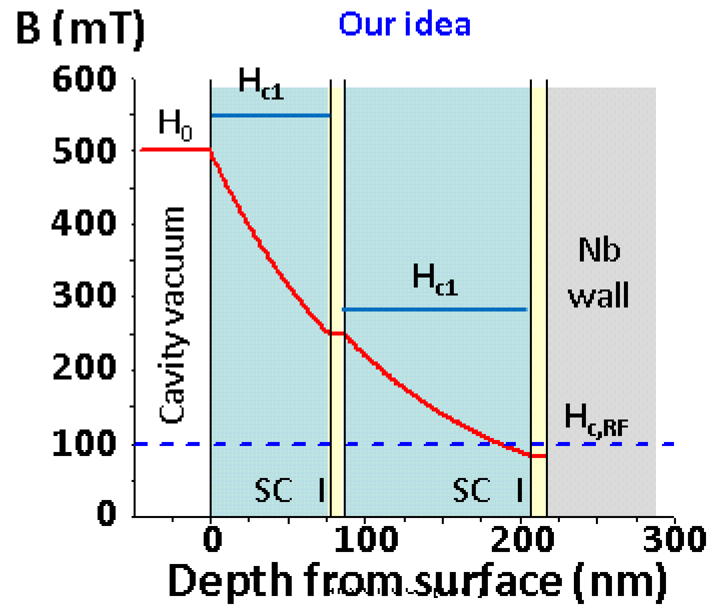
E_{acc} = 100 MV/m

Lower T_c (low quality film)

[Beringer, Thin film workshop, JLAB, 18-20 July 2012]

There is a possibility that we can achieve ~500 mT (E_{acc} ~125 MV/m) even with 2 layers of MgB_2



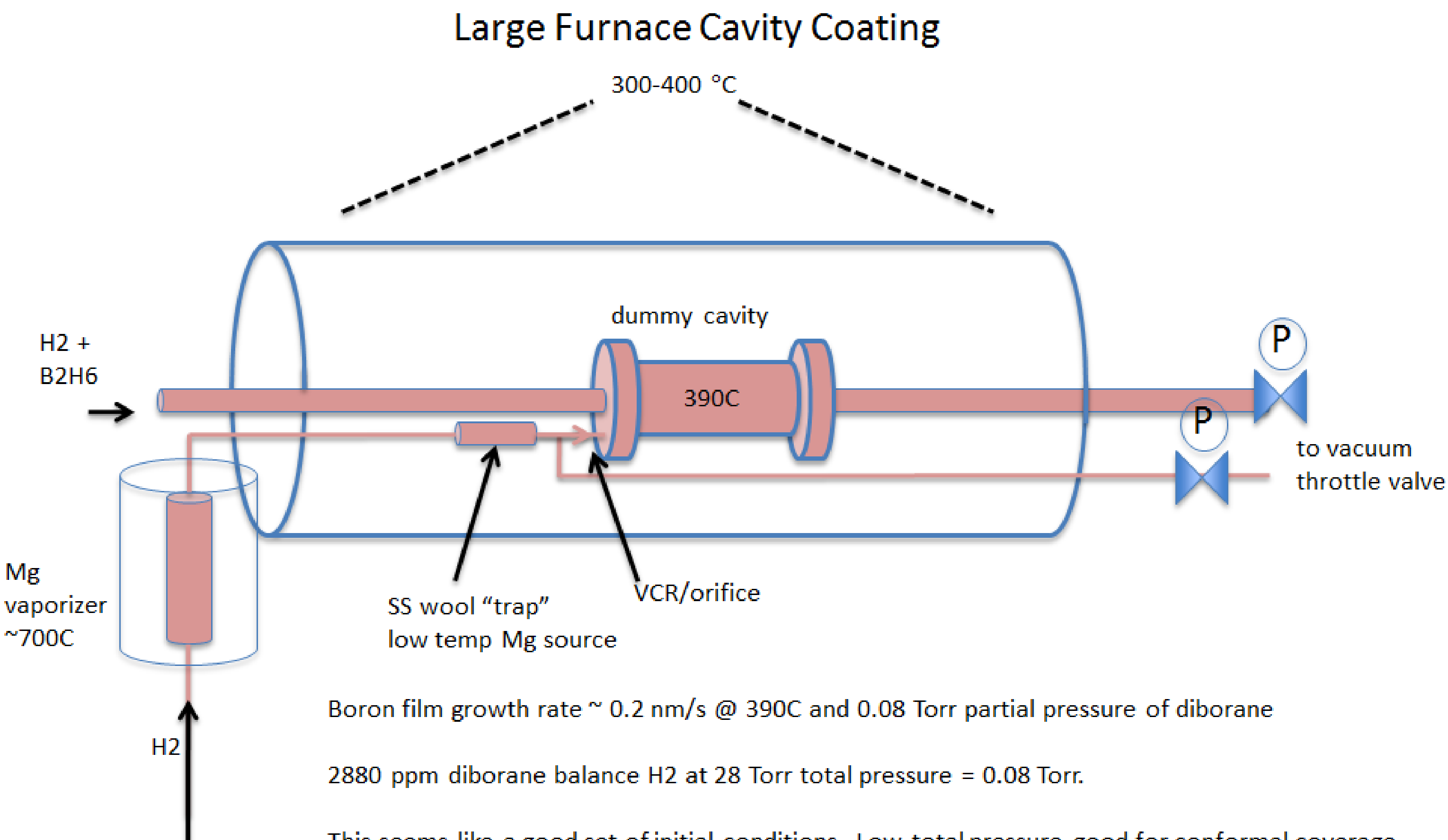


<u>Fixed thickness multilayers</u>:
- $d \le$ 77nm for $H_{c1} \ge$ 5500 Oe
- 3 layers needed
- coating curved walls with very thin uniform of layers is challenging

<u>Variable thickness multilayers</u>:
- $d_1 \le$ 77nm for $H_{c1} \ge$ 5500 Oe
- only 2 layers needed
- 2nd layer is thicker: 100nm $\le d_2 \le$ 120nm

[Tajima et al., SRF2011]

At LANL, 2-stage coating, i.e., B layer using diborane (B_2H_6), then react it with Mg vapor, is being tried

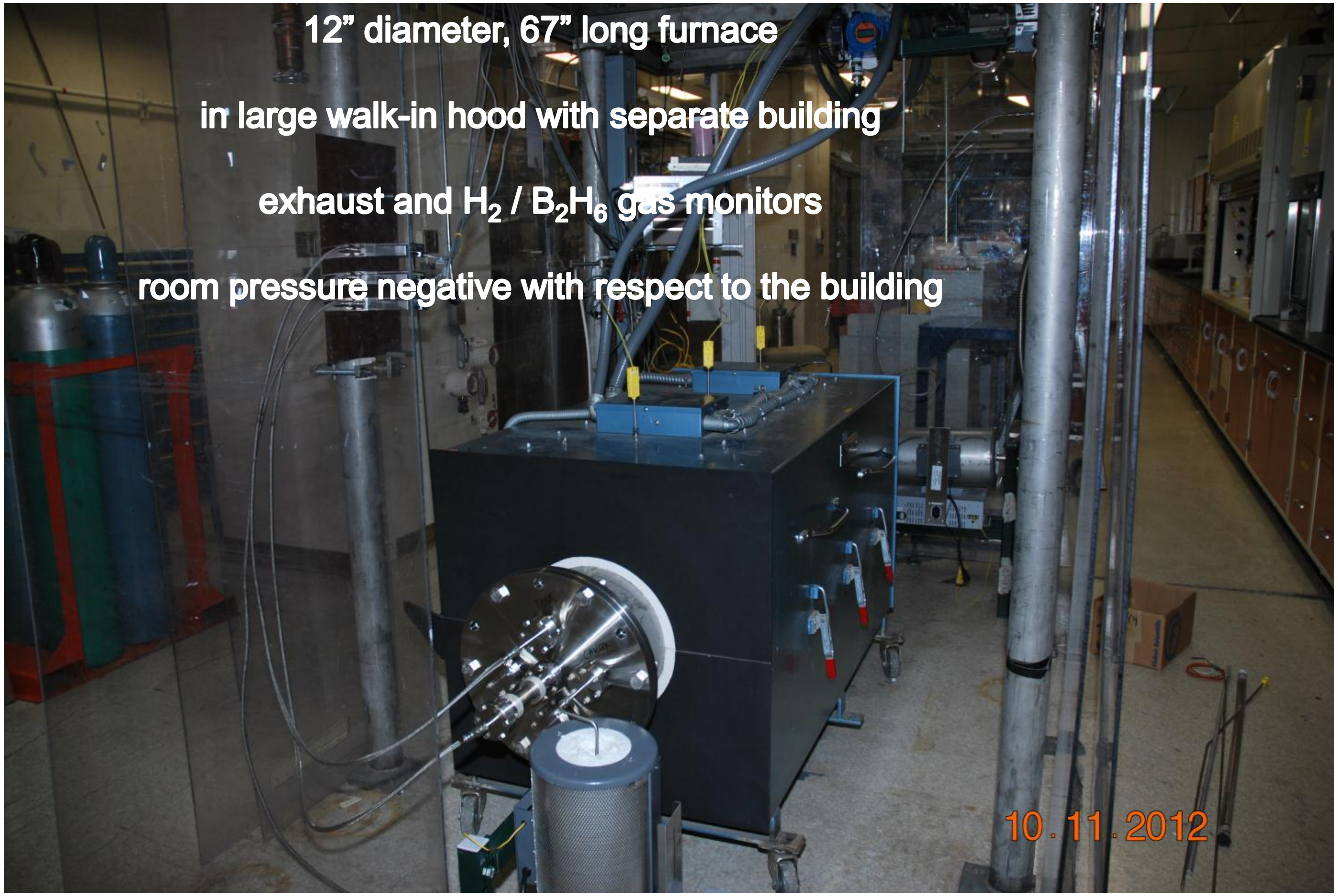


Boron film growth rate ~ 0.2 nm/s @ 390C and 0.08 Torr partial pressure of diborane

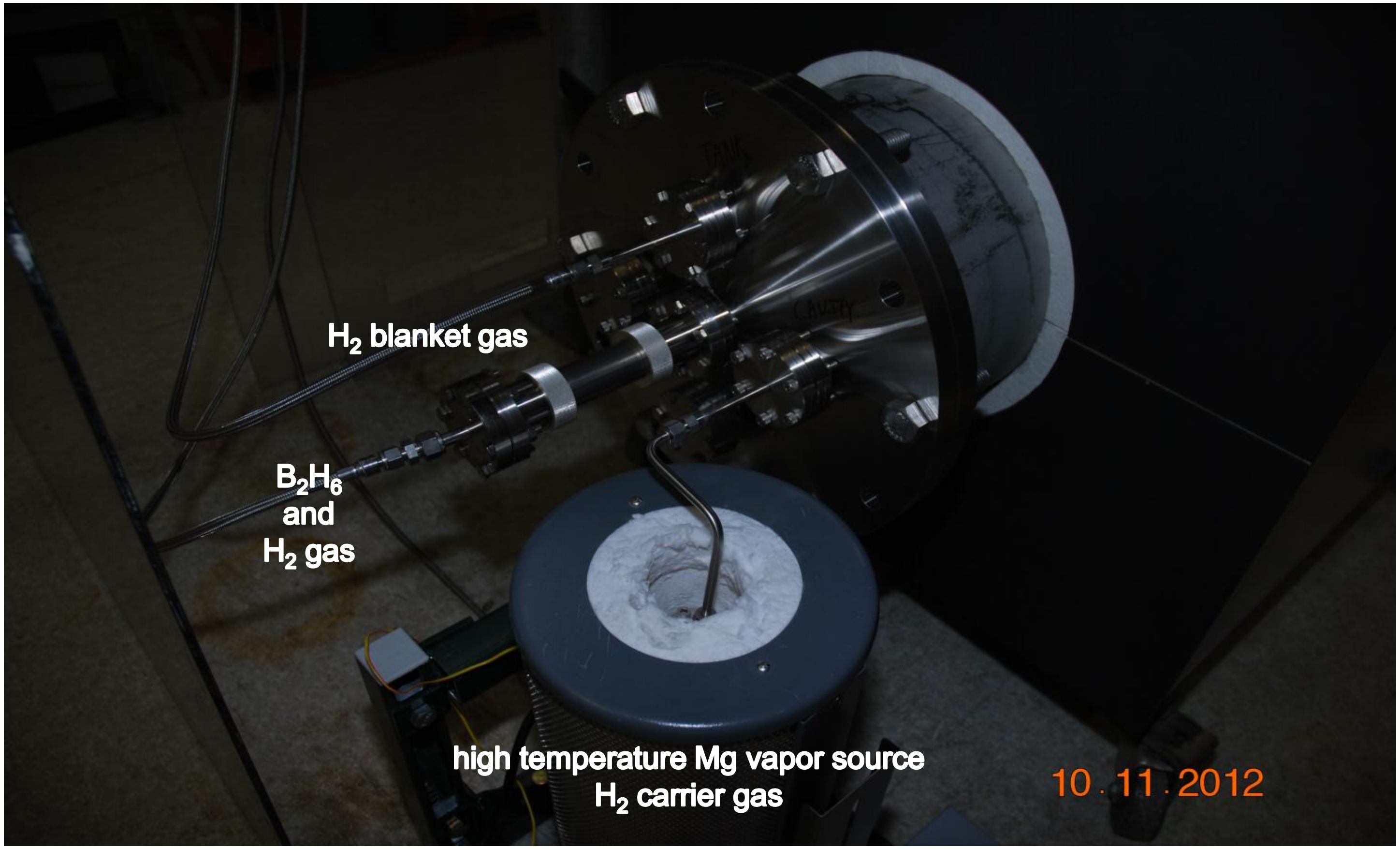
2880 ppm diborane balance H2 at 28 Torr total pressure = 0.08 Torr.

This seems like a good set of initial conditions…Low total pressure good for conformal coverage.

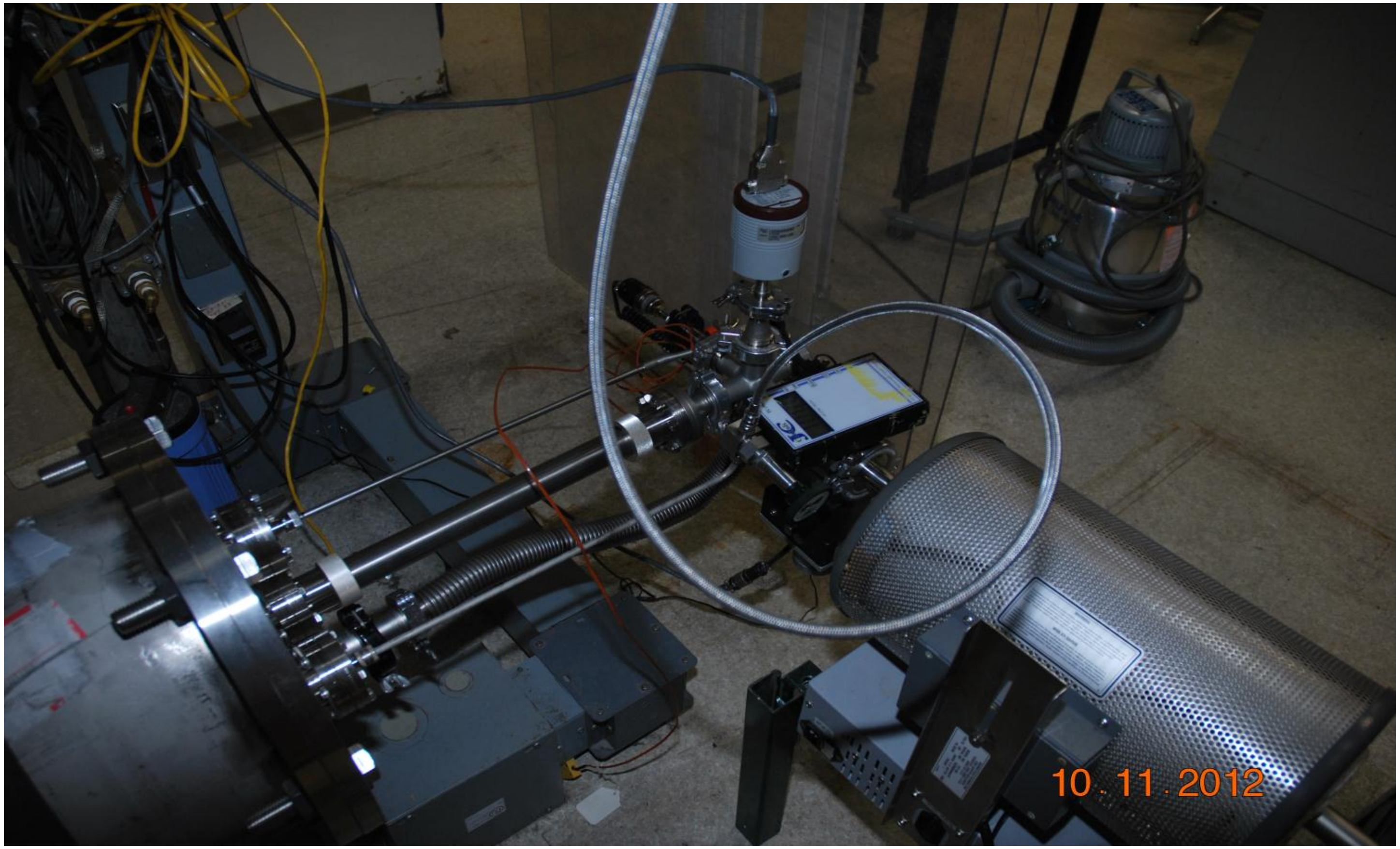
MgB_2 CVD reactor for a 1.3 GHz cavity located at Technical Area 35



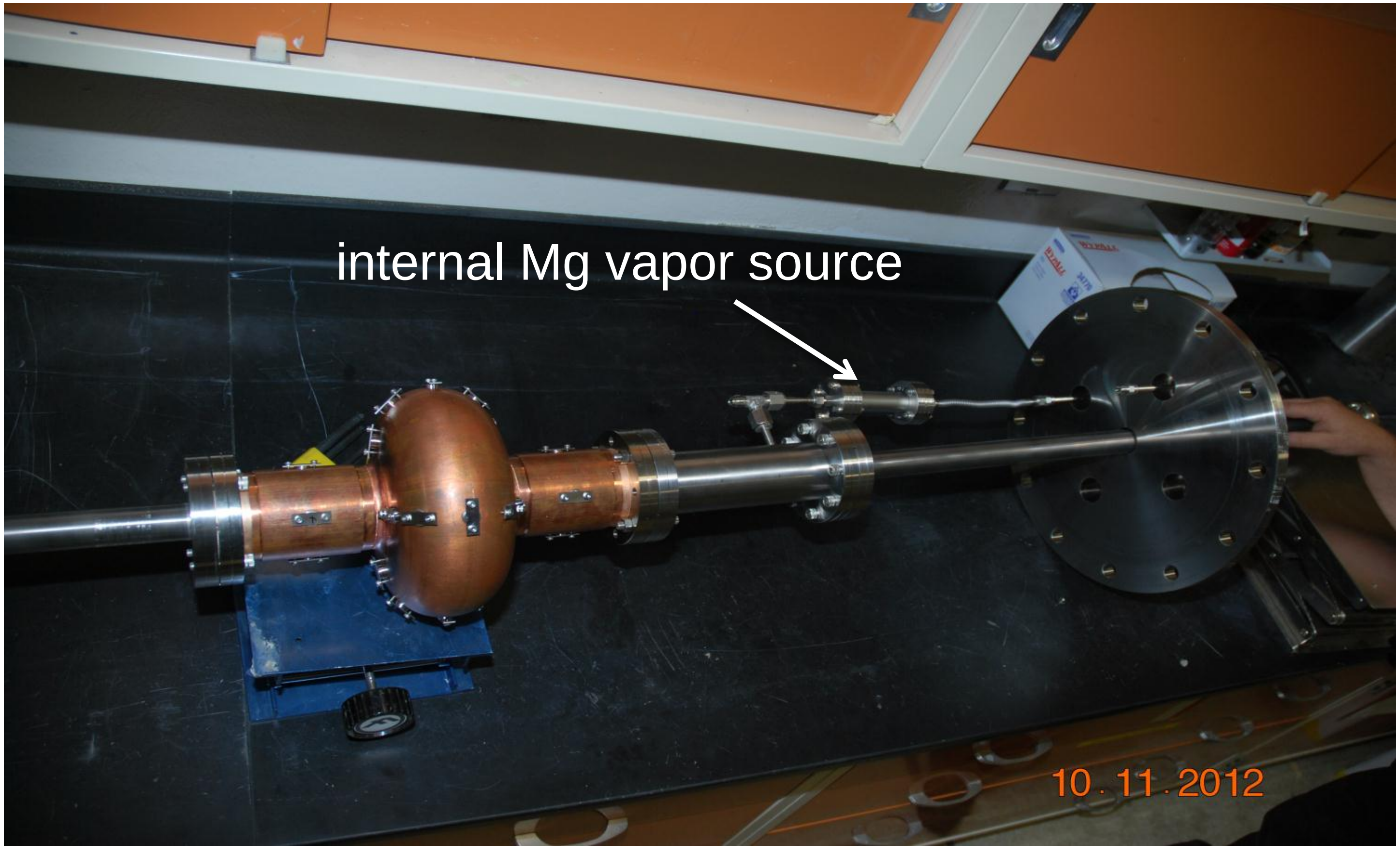
Gas delivery and external Mg vapor source



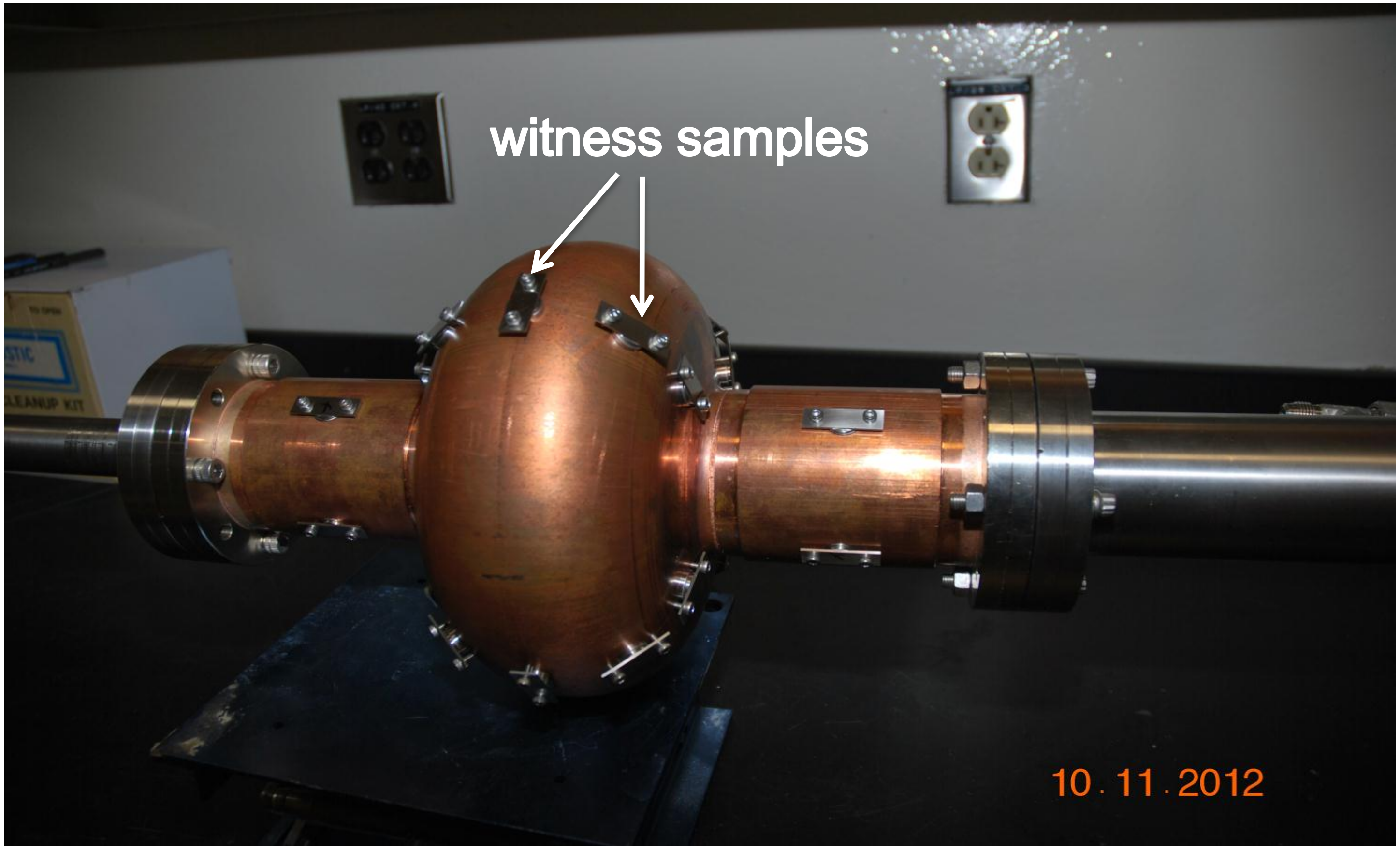
Exhaust system with excess di-borane burner



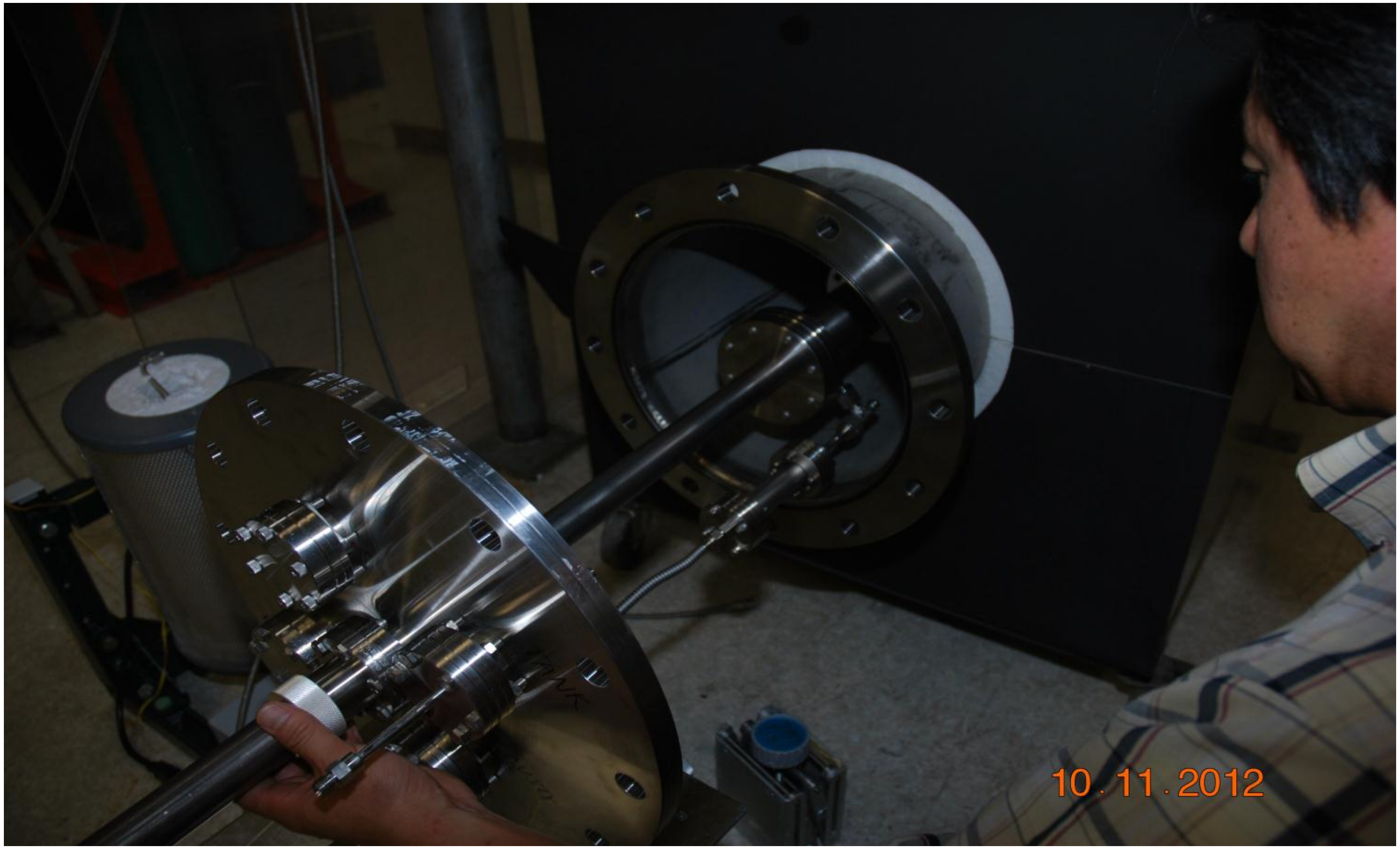
Mounting test cavity



Copper surrogate cavity with 28 holes for samples. First substrates will be 6 mm x 6 mm x 0.43 mm sapphire



Cavity installation into furnace



Our plans and milestones for MgB_2 coating

- **Achieve superconductivity with witness samples by 30 May 2013**
- **Optimize coating parameters to get high-quality films by 31 July 2013**
- **Optimize coating parameters to get good uniformity on cavity surfaces by 30 September 2013**
- **Coat 1.3 GHz single-cell cavities and test them after that. (Cavities to be coated will be either Nb/Cu or Nb cavities)**
- **We are currently considering ALD for dielectric coating (Al_2O_3 or other material)**

Seamless cavity fabrication

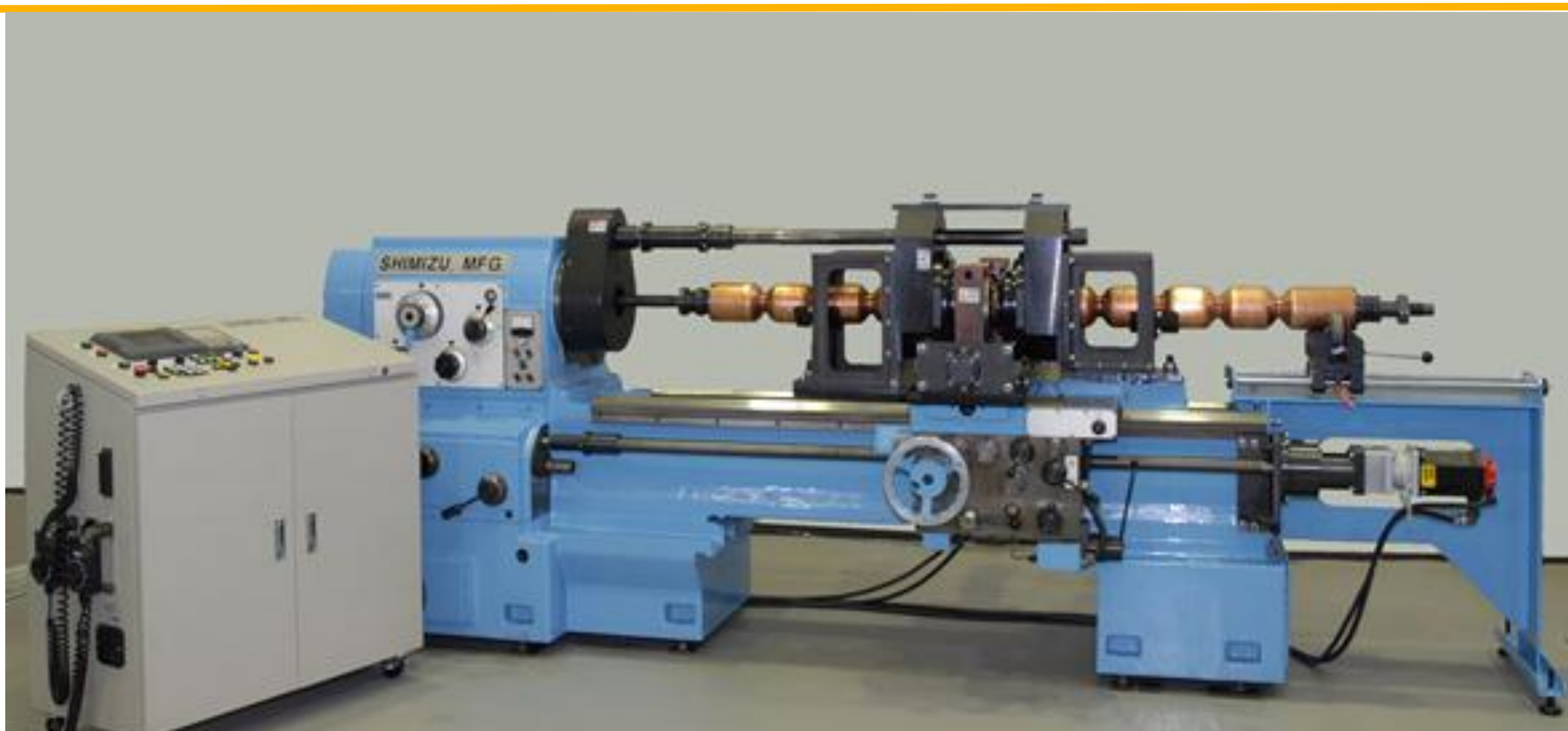
In collaboration with KEK and FNAL

I was at KEK as an invited investigator from April 2011 through March 2012

Status of copper forming at KEK

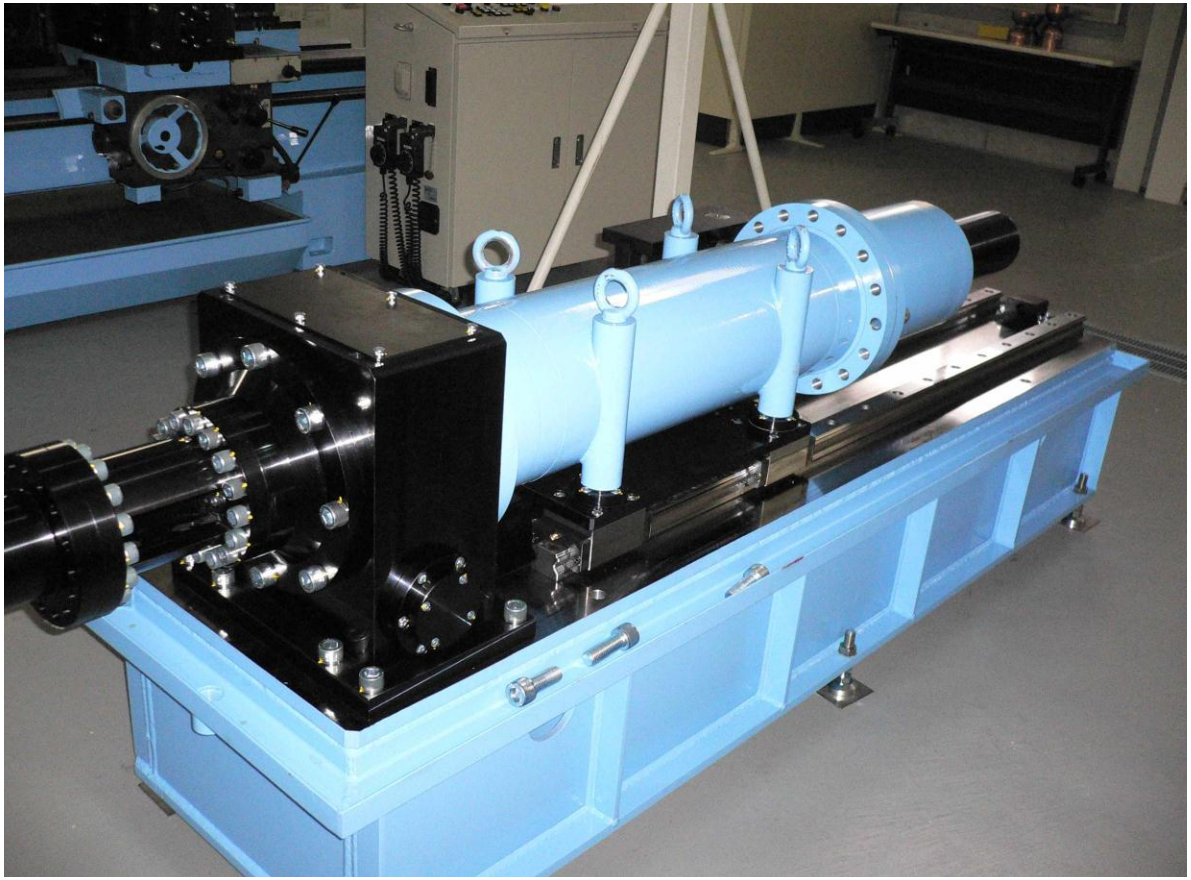
- **Use of C1020 copper seamless tubes (130 mm OD, 3-4 mm-thick) from Hitachi Cable Co., Ltd.**
  - Manufacture of copper seamless tubes is an established process in industry.
  - Very inexpensive
    - X50 cheaper than RRR300 Nb sheets.
    - X100 cheaper than appropriate Nb seamless tubes (~$180 vs. ~ Nb $17,300 for a 800 mmL, 3 mm-thick tube appropriate for cavity cell forming)
  - Nb films comparable with high-RRR bulk Nb might be available soon
- **KEK has been successful in forming 3-cell cavities from these tubes with 500 °C x 2 h vacuum annealing before forming.**

Necking machine at KEK. The length is optimized for an ILC-type 9-cell cavity



Ueno et al., Kasokuki Gakkai, 2007.

Hydroforming machine at KEK.   The existing machine cannot form more than 3 cells.

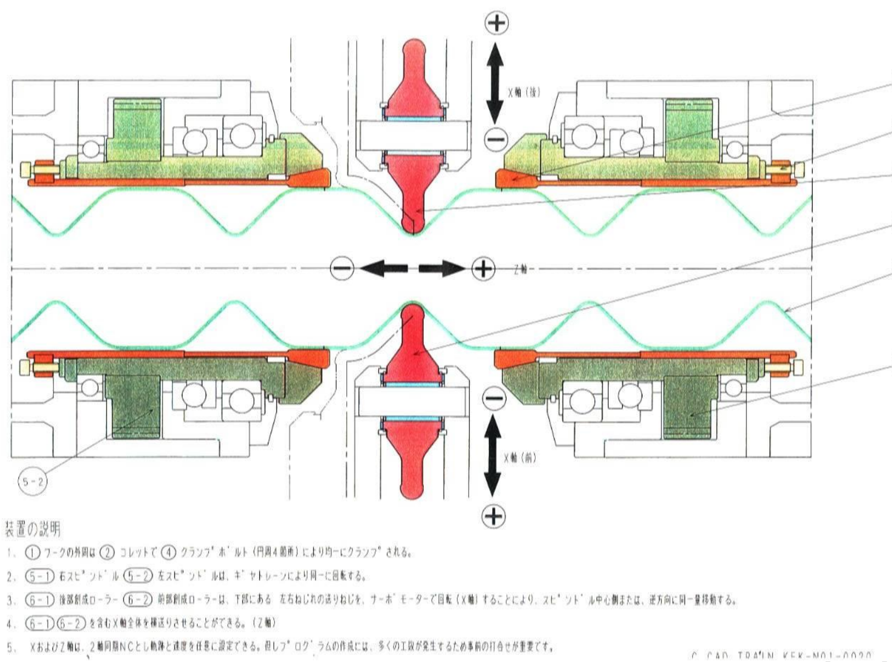


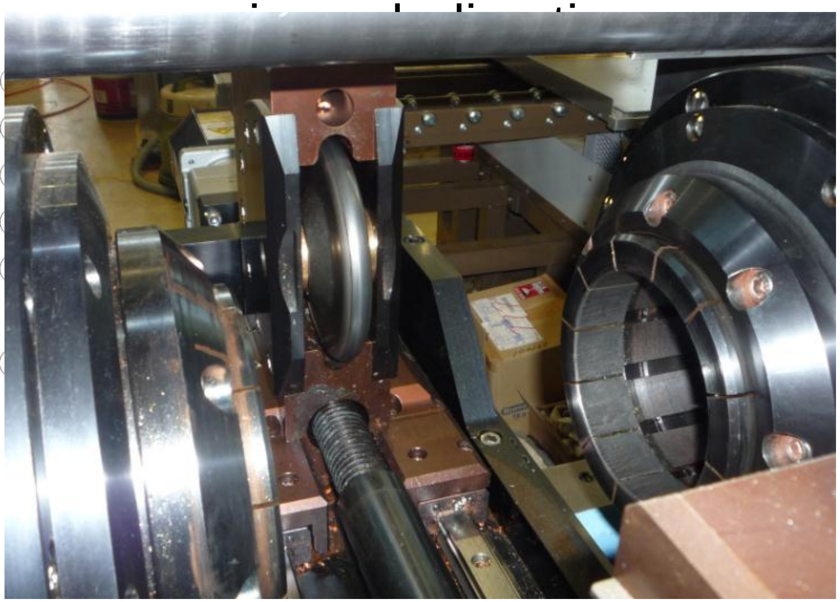
Ueno et al., Kasokuki Gakkai, 2006

Detail of KEK forming process

Necking

The pipe rotates at 200 rpm, the moving speed of the roller is 150 mm/min axially and its movement is controlled by NC.





Ueno et al., Kasokuki-Gakkai, 2007

Some photos from the process to hydroform a copper 3-cell ILC baseline shape

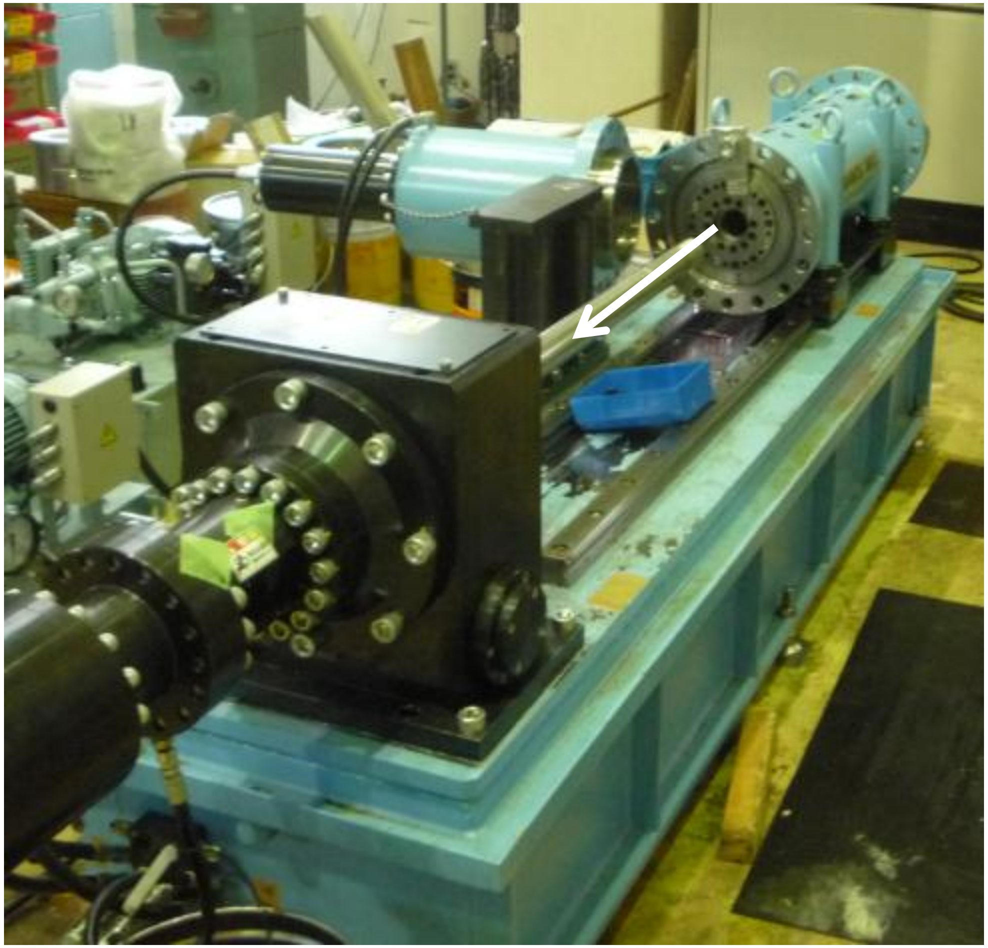
After the first hydroforming using an intermediate constraint dies

Attach final dies

Attach final dies

Inserted into the cylinder

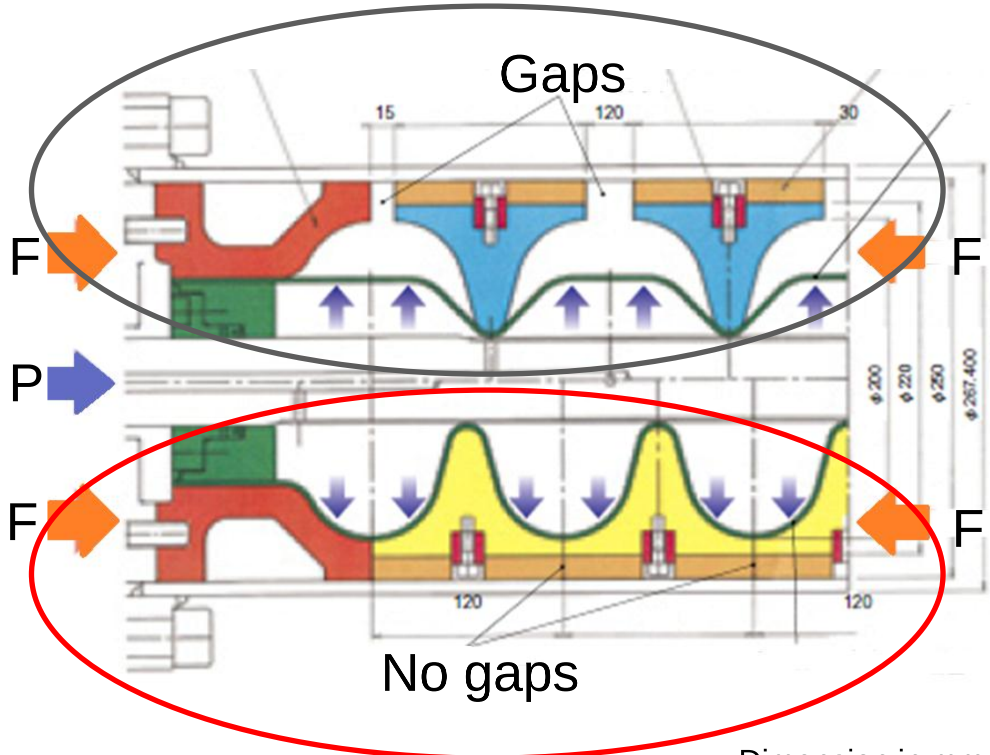
To be attached to the hydroforming machine



Hydroforming procedure at KEK (in the case of copper)

- **Start with 8 MPa, axial speed is 20-50 mm/min. Try to leave 5-8 mm radial gap between the deformed cell and the die before 2 dies make contact.**
- **After putting 2 dies together, raise the pressure to 25 MPa for the cells to conform to the dies completely. (From looking at the pressure gauge, it looks like the pipe is being deformed at a pressure 9-13 MPa.)**

Before forming



Dimension in mm

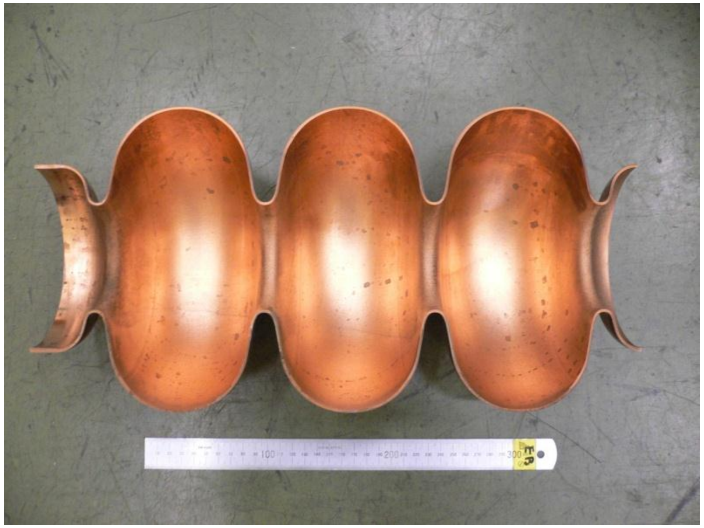
After forming

After forming. Conformed to the die very well.

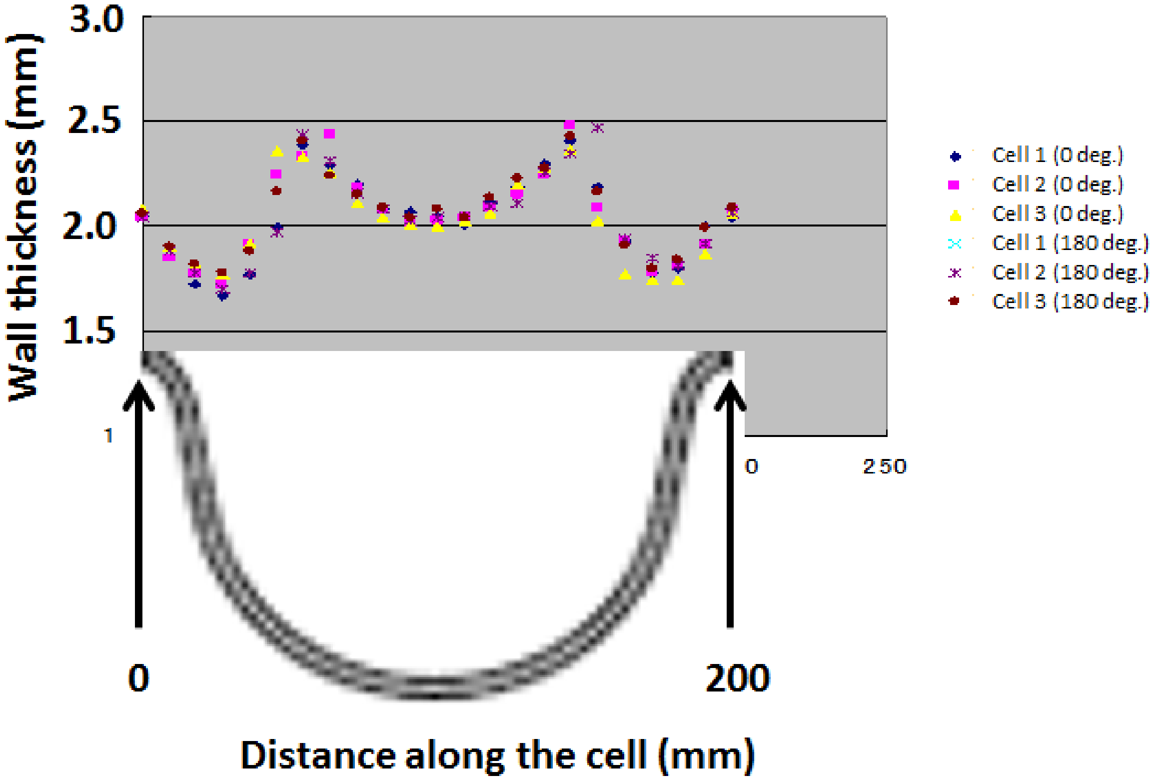
After forming a 3-cell cavity

The starting thickness of 3 mm seems not enough ⇒ changing to 3.5 mm and 4 mm tubes

Initial material: Oxygen Free Cu (C1020) seamless pipe from Hitachi Cable Co.



An ILC baseline-cell-shape cavity formed in May 2011 by Hitoshi Inoue



- Annealing at 500 °C for 2 hours between necking and hydroforming

Status of Nb forming at KEK

- Nb is difficult due to much less ductility than copper
- Few vendors that can supply seamless tubes adequate for cavity forming
- FNAL will soon provide KEK with some tubes from ATI Wah Chang, a vendor that was able to produce some formable tubes in the past
- Collaboration with a Japanese vendor is ongoing, but has not been successful in producing an appropriate tube yet.

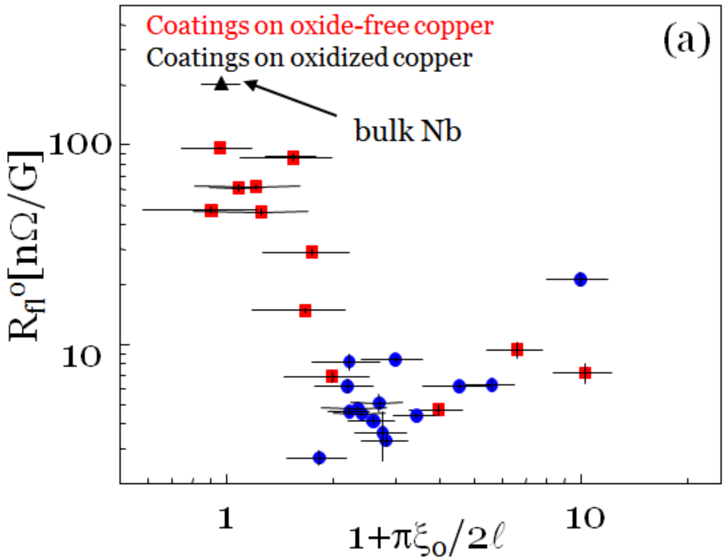
New Nb films coated on copper cavity

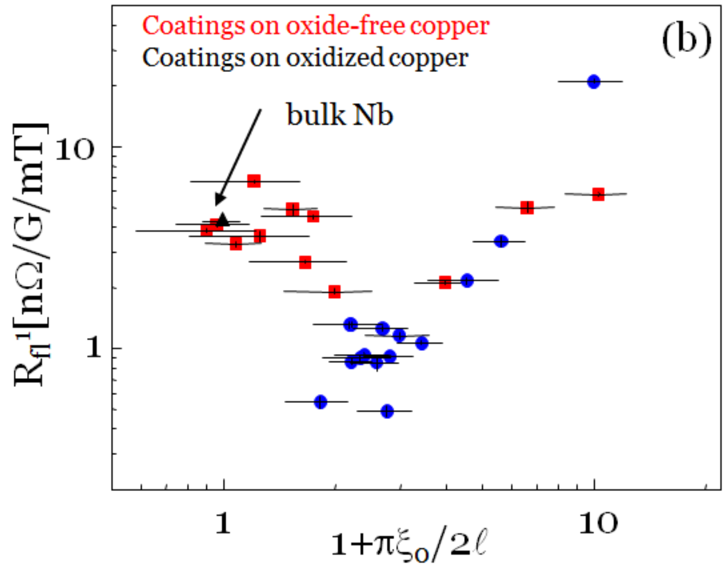
In collaboration with AASC and KEK

Advantages of using copper cavity with Nb coating

- **Cheaper (x50 less than RRR~300 Nb)**
- **Due to high thermal conductivity of Cu, surface temperature is lower than bulk Nb $\Rightarrow$ more stable against quench**
- **Residual resistance less sensitive to external magnetic field**

$$R_{fl} = (R_{fl}^{0} + R_{fl}^{1} H_{RF}) H_{ext}$$





Calatroni, TTC meeting, JLAB, 07 November 2012.

As many of us know, while Nb/Cu cavities were successful for LEP at CERN, sputtered Nb films have strong Q_0 slope

State-of-the-art 25 years ago

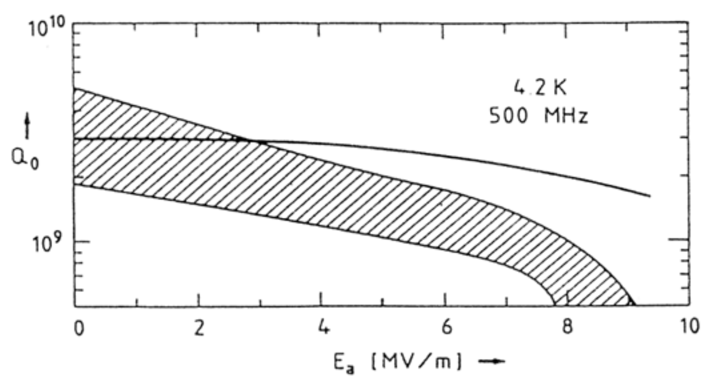
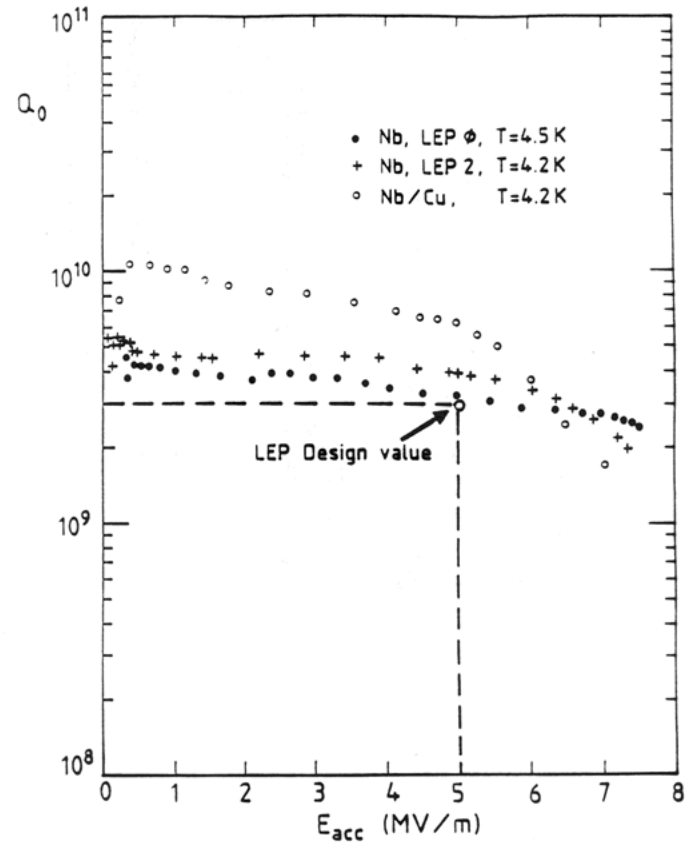


Figure 1. Typical $Q(E_a)$ curves of sheet metal (line) and sputter coated cavities (hatched).



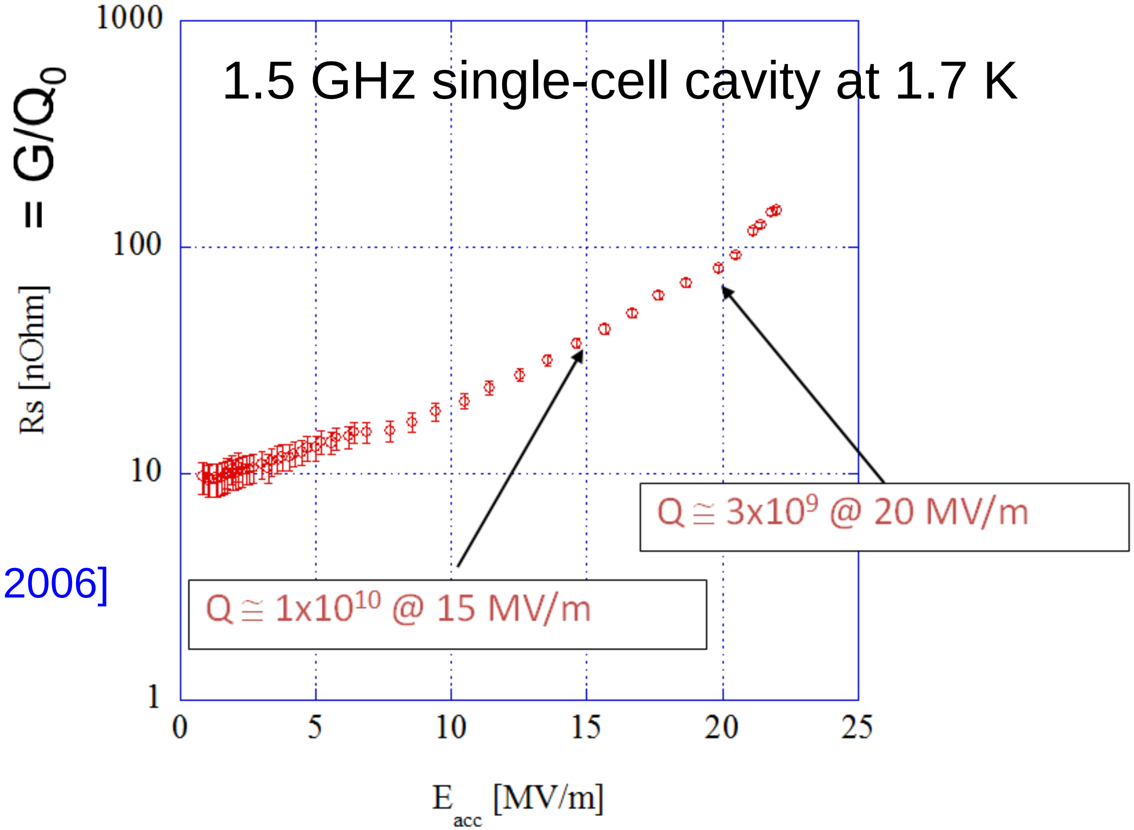
[Calatroni, Thin film workshop, Padua, 2006]

Parameter optimization led to ~28 MV/m, but a strong Q_0 slope still exists

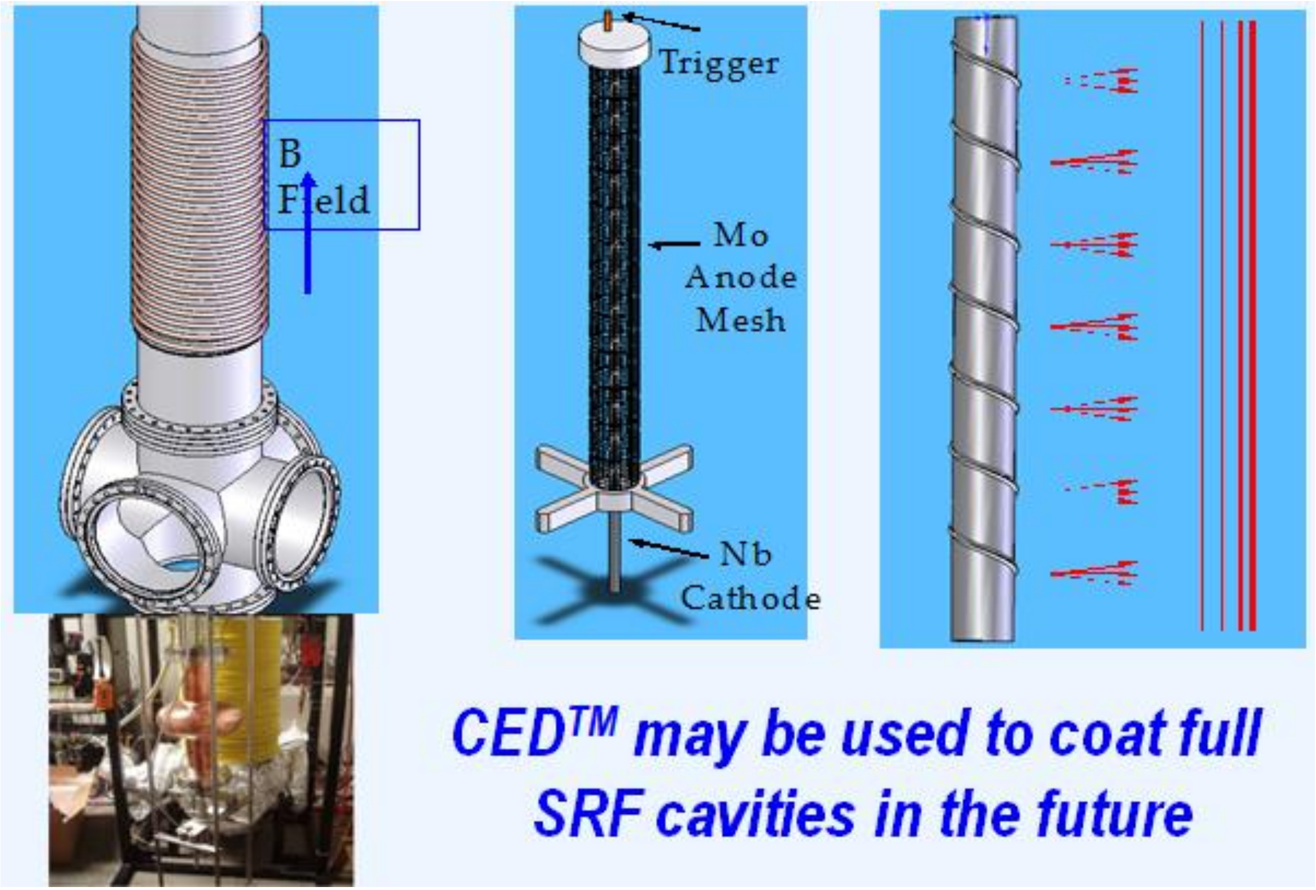
State-of-the-art 5 years ago

The reported highest gradient for Nb/Cu cavities so far is 28 MV/m

[Calatroni, Thin film workshop, Padua, 2006]



Coaxial Energetic Deposition (CED™) by Alameda Applied Sciences Corporation (AASC), San Leandro, California, USA



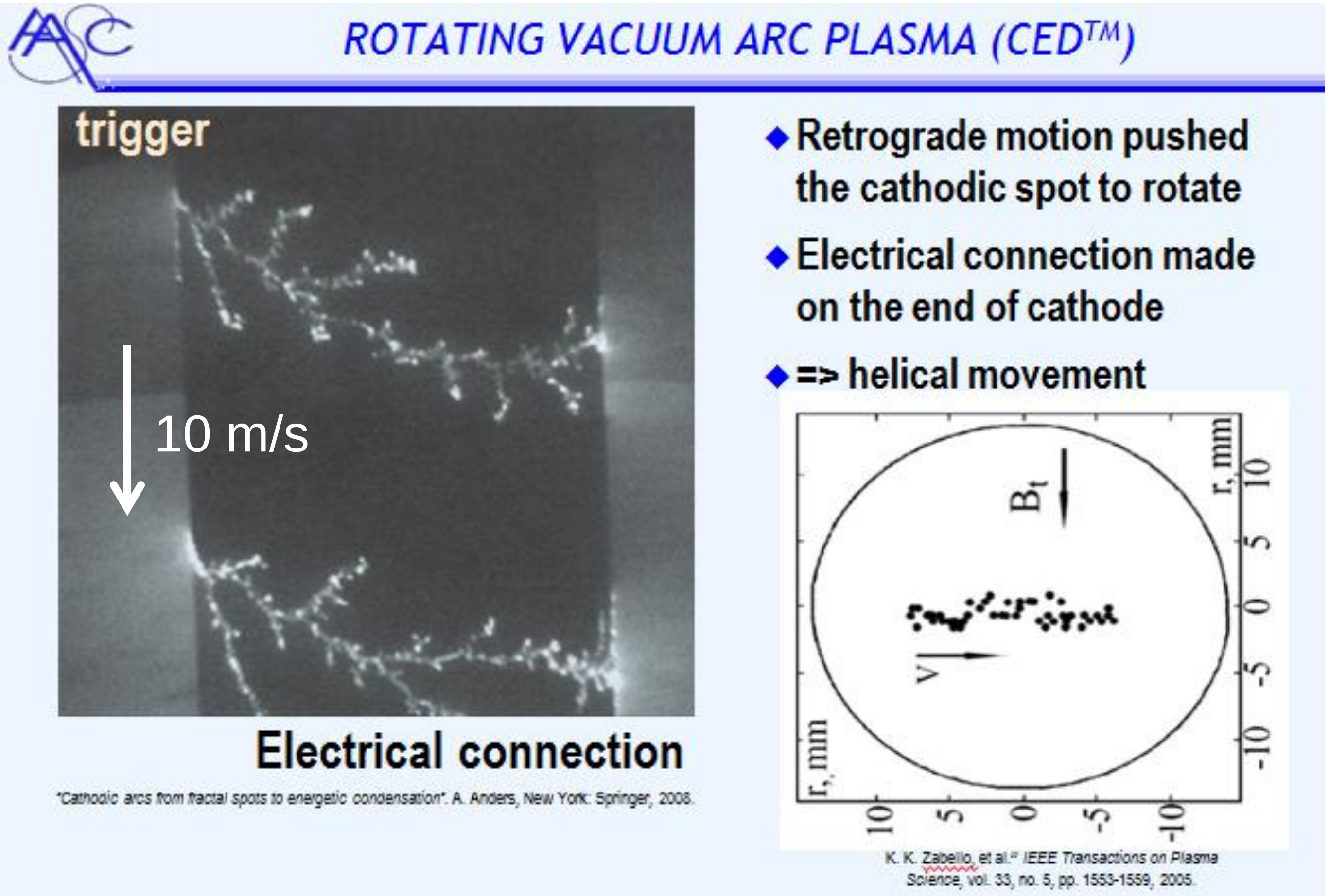
[E. Valderrama et al., CEC-ICMC2011, Spokane, WA, 13-17 June 2011]

Coaxial Energetic Deposition (CED™) by AASC [Krishnan et al., PR-STAB 15 (2012) 032001]

Base pressure after 120 °C bake ~5 x 10^{-8} Torr

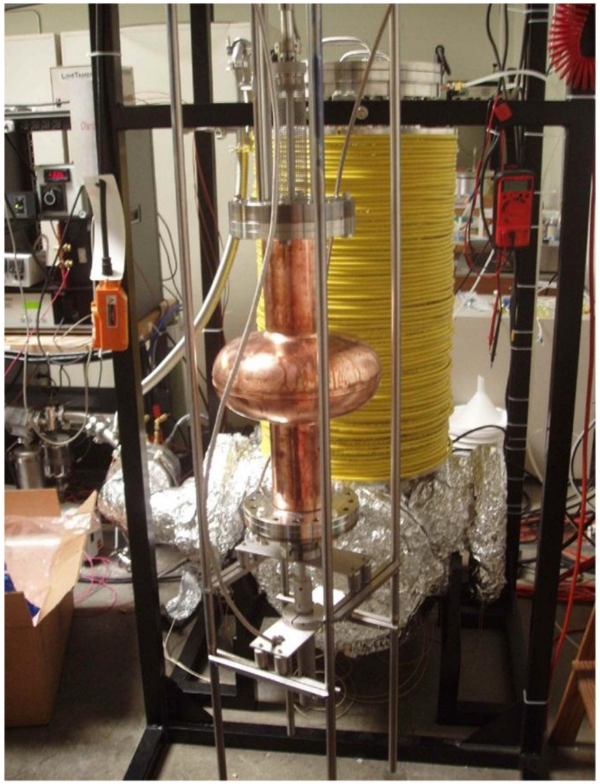
High RRR films

Needs ~4000 pulses for 1 μm coating

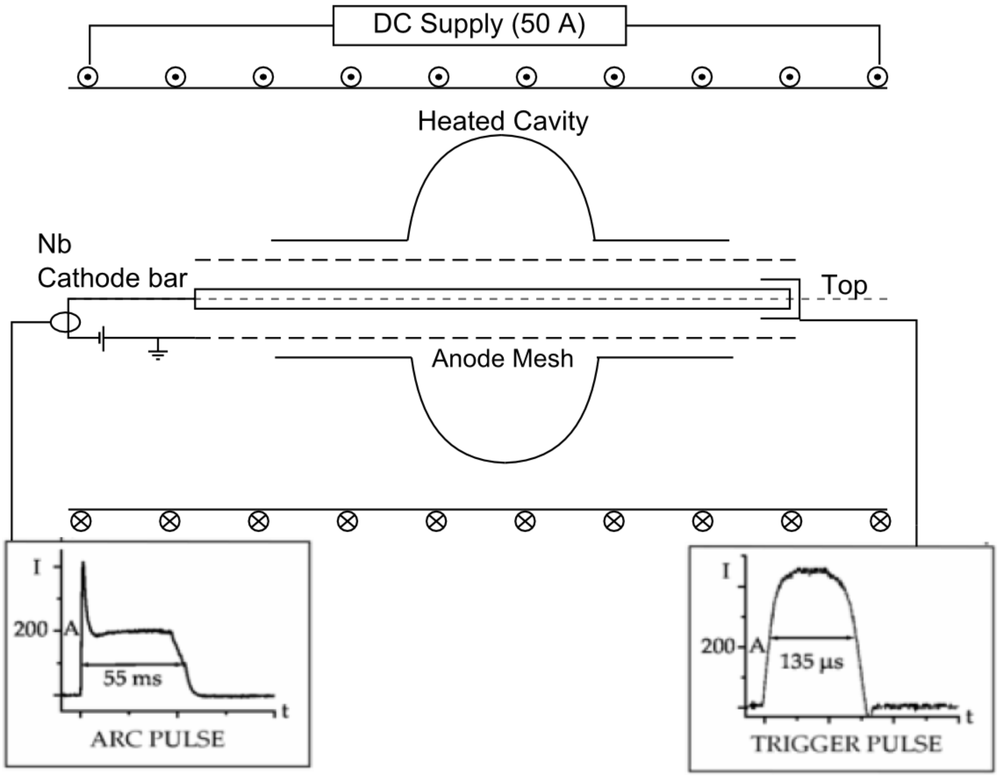


[E. Valderrama et al., CEC-ICMC2011, Spokane, WA, 13-17 June 2011]

Arc source is scalable to high throughputs for large scale cavity coatings. Present version deposits ~ 1 monolayer/pulse ~ 1 ms UHV and clean walls are important

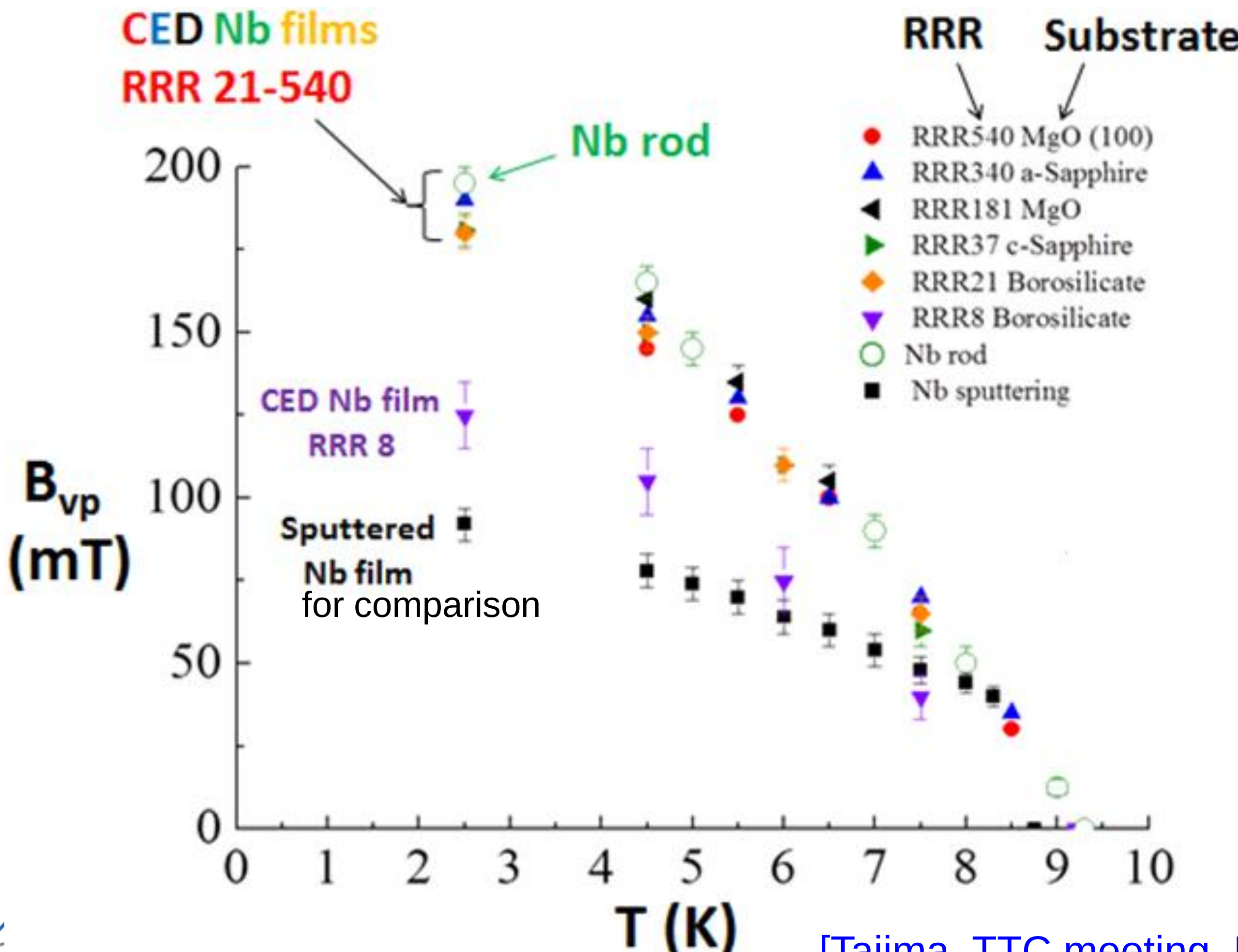


Coaxial Energetic Deposition (CED™)



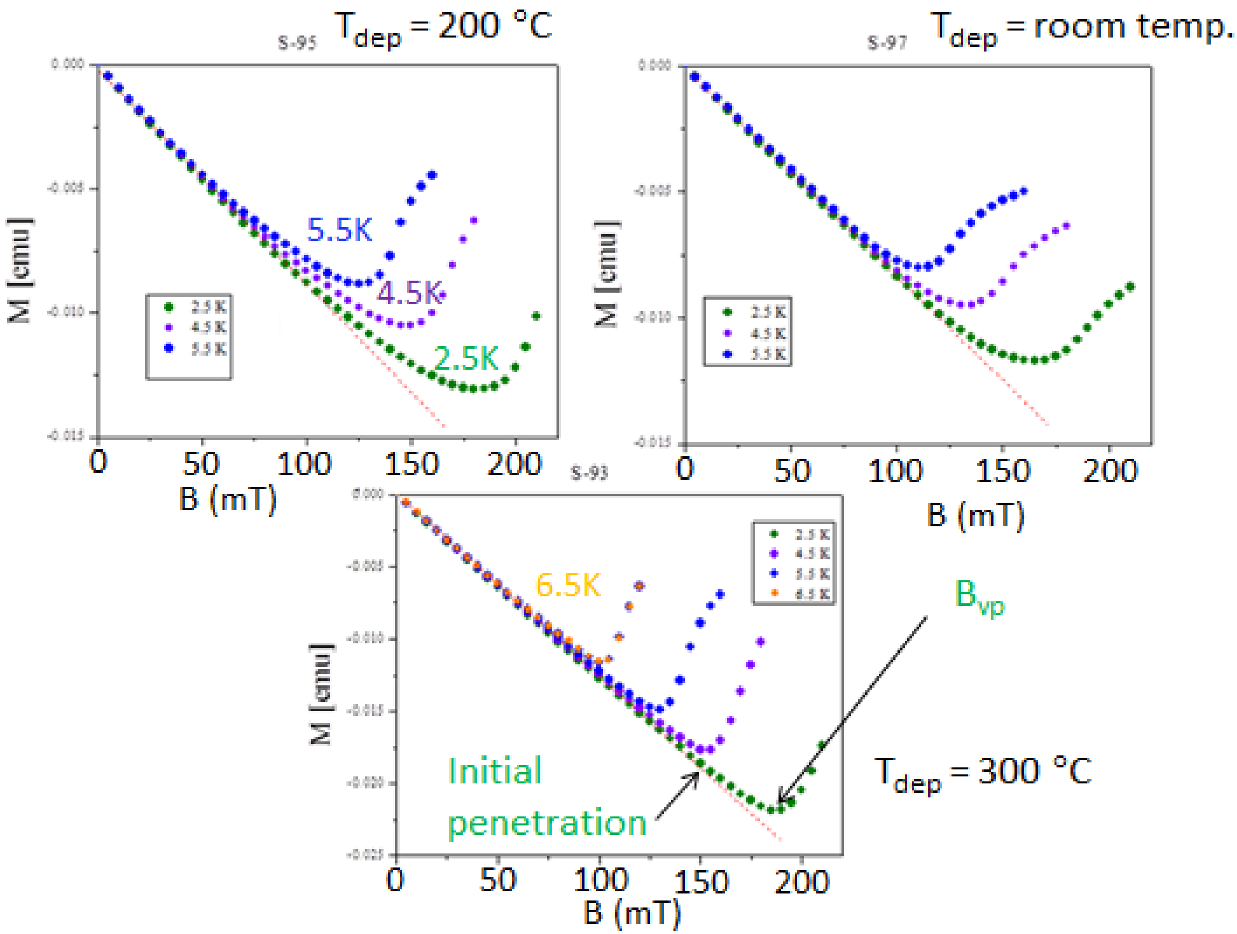
[Colt James et al., ASC2012, Portland, 7-12 Oct. 2012]

B_{vp} of CED Nb films coated on dielectric substrates have shown values comparable with RRR~300 Nb



[Tajima, TTC meeting, Beijing, 5-8 Dec. 2011]

Magnetization measurements of CED Nb films coated on Cu

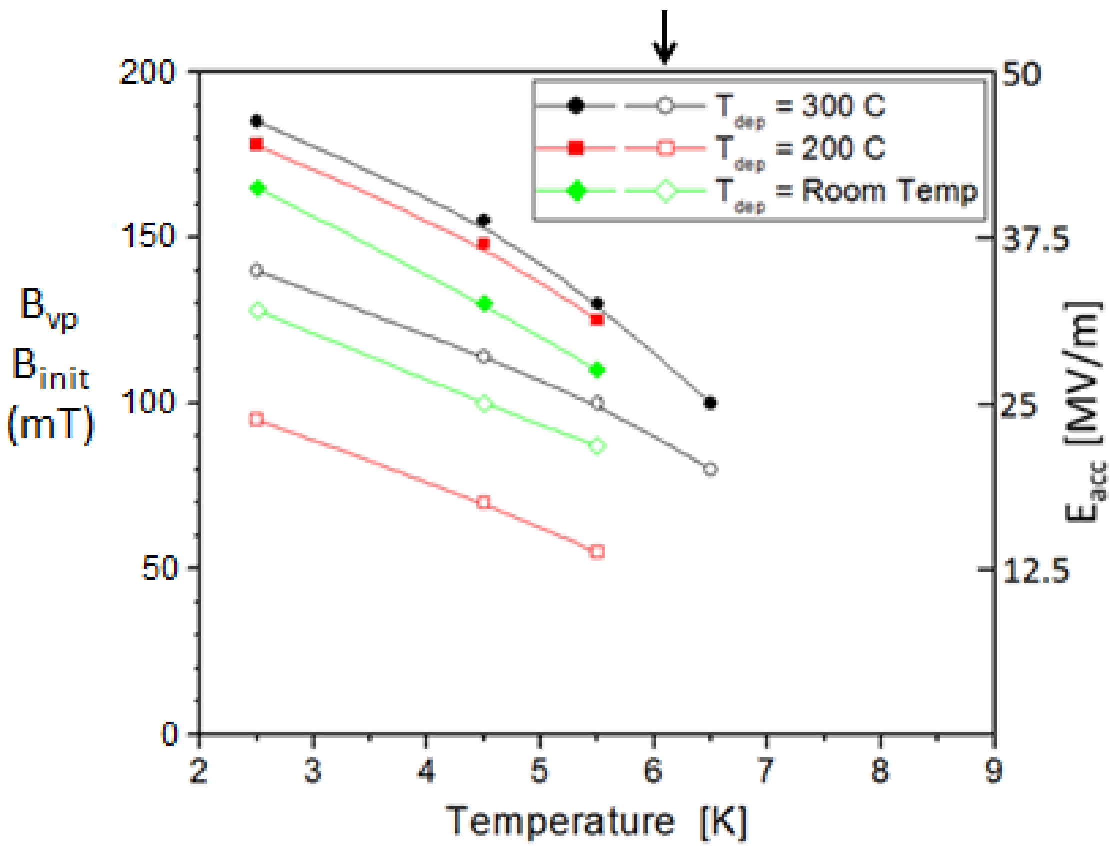


[Civale et al., to be submitted to a journal with more recent data]

UNCLASSIFIED

Summary of magnetization measurement results of CED Nb films coated on Cu

Initial vortex penetration (2 % deviation from Meissner slope)



[Colt James et al., ASC2012, Portland, 7-12 Oct. 2012] modified

Coating of 1.3 GHz single-cell copper elliptical cavity with a CED Nb film

3-cell cavity was formed from a seamless copper (C1020) pipe at KEK

Cut into 3 single cells and beam pipes were EB-welded and SST flanges were brazed.

Being used as a surrogate cavity for MgB_2 coating tests

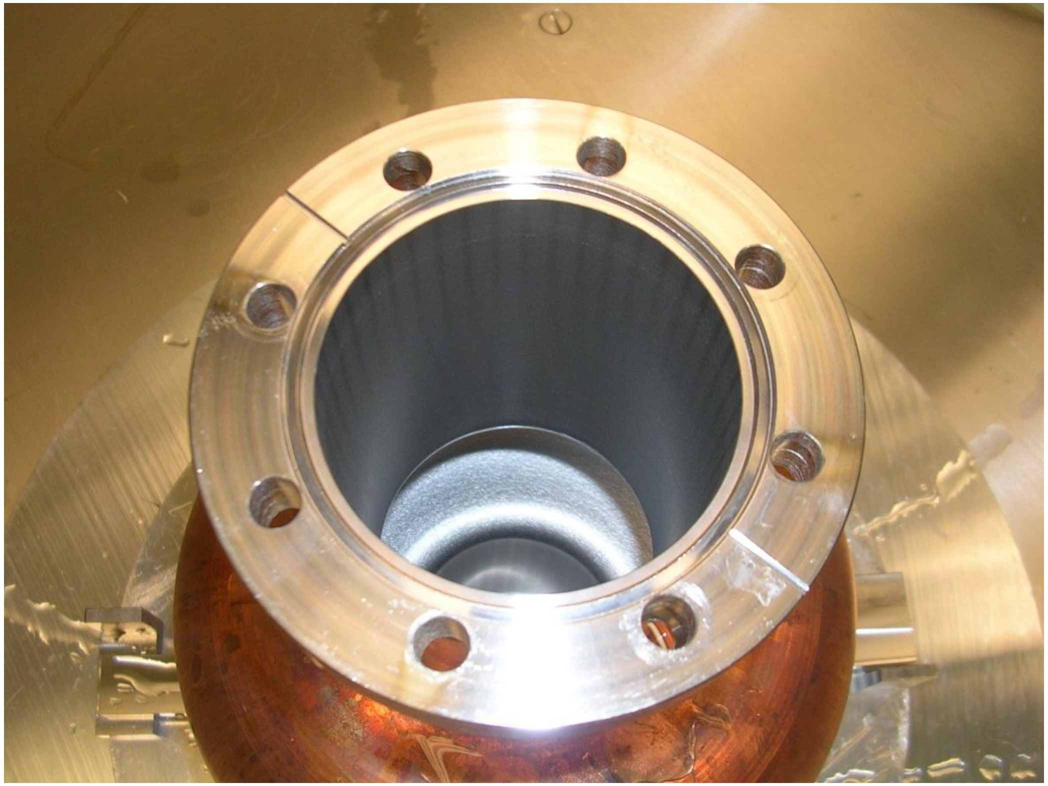
Being used for CED Nb coating tests

Coating of 1.3 GHz single-cell copper elliptical cavity with a CED Nb film (cont.)

- At LANL, Cu cavity was chemically etched, high-pressure rinsed with ultra-pure water, pumped down, baked at 50-60 °C, filled with filtered N_2 gas and shipped to AASC.
- AASC coated it at 350 °C to a thickness of ~5 μm and shipped back to LANL.
- At LANL, the cavity was HPR'ed at 500 psi for a total of 2 hours in a class 100 clean room, assembled with flanges and couplers and tested. No baking.

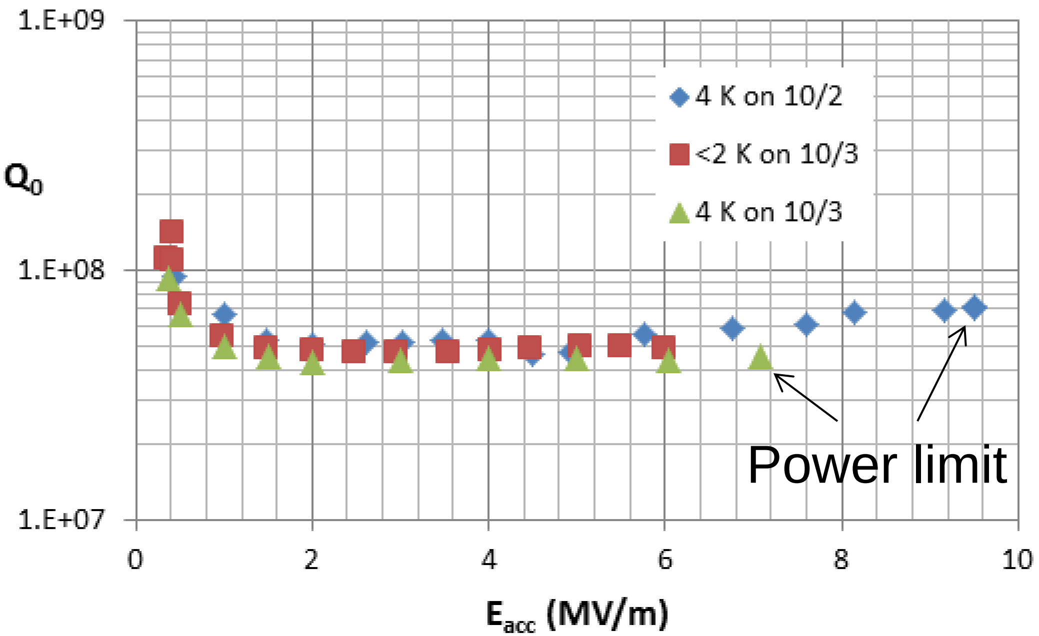
[Colt James et al., ASC2012]

After ultra-pure water rinsing at 500 psi for 1 hour in the SRF lab clean room at LANL



The beam pipe (120 mm long) was found to be too short to eliminate the effect of RF losses on the SST end flanges, but it did not quench up to available power limit (~9.5 MV/m)

Q_0 was dominated by the losses on the end flanges.



This result was predicted before the test by MWS calculations and it was verified by this test.

Next steps for Nb/Cu cavity development

- KEK fabricated 3 new hydroformed copper cavities with 170 mm (50 mm longer than existing) beam pipes to eliminate the effect of end SST flanges.
- KEK will send them to LANL by early March 2013.
- These cavities will be coated with Nb at AASC in March 2013.
- They will be tested at LANL in April 2013.
- Some of these cavities will be used for MgB_2 coating if they are good.

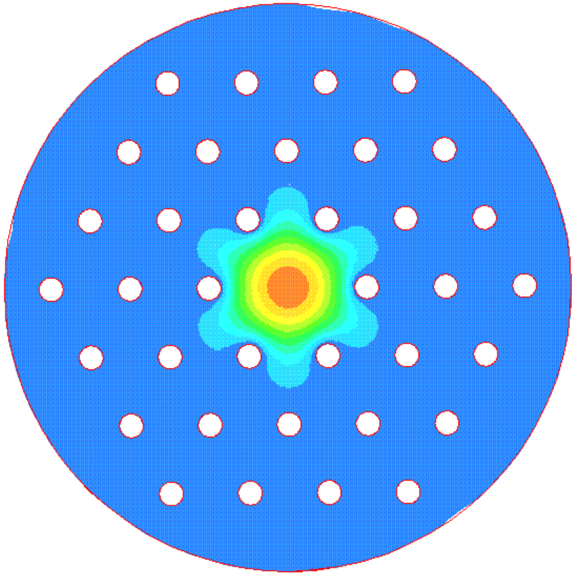
Superconducting photonic band gap (PBG) cavity development

Led by Evgenya Simakov

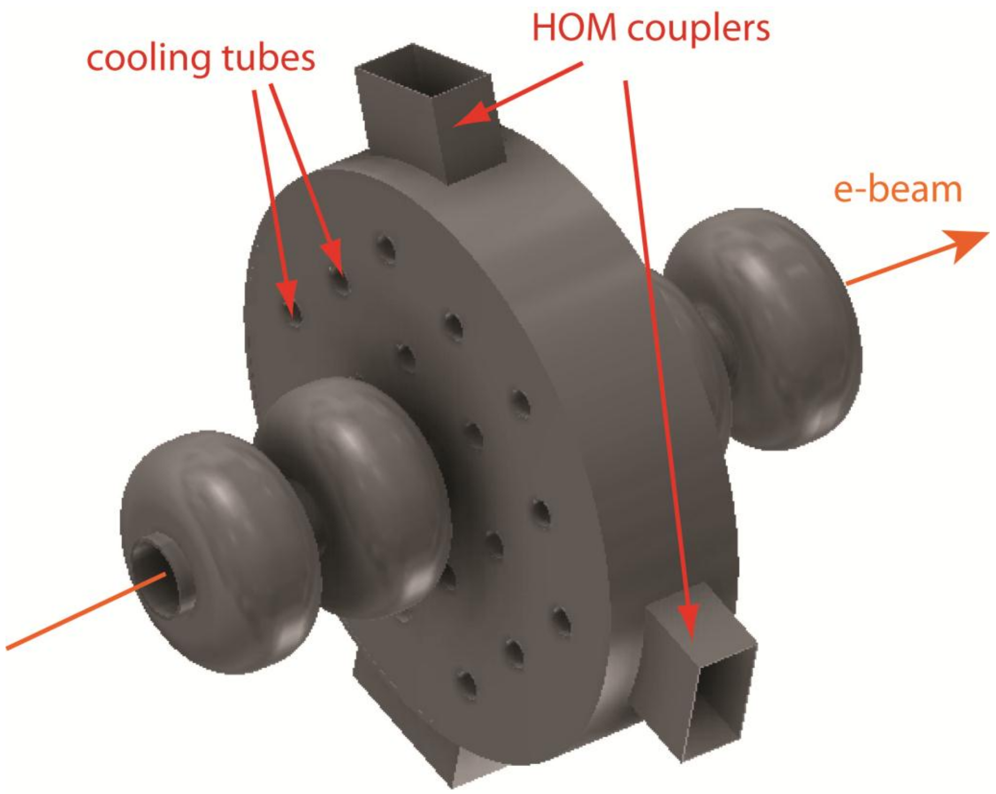
Funded by DOE SC/HEP and ONR

Effective for HOM damping without sacrificing real estate gradient

Confines single mode TM_{01}

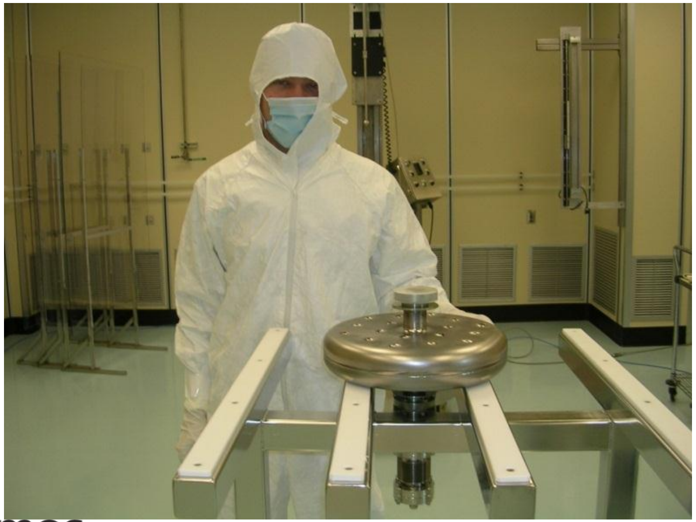


$Q_{ex,\ HOM} < 115$

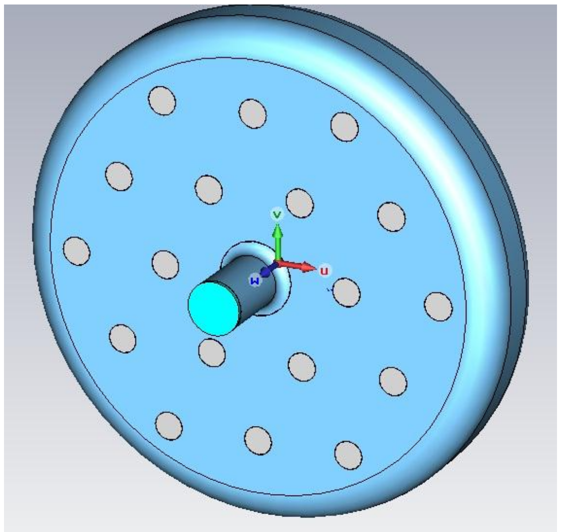


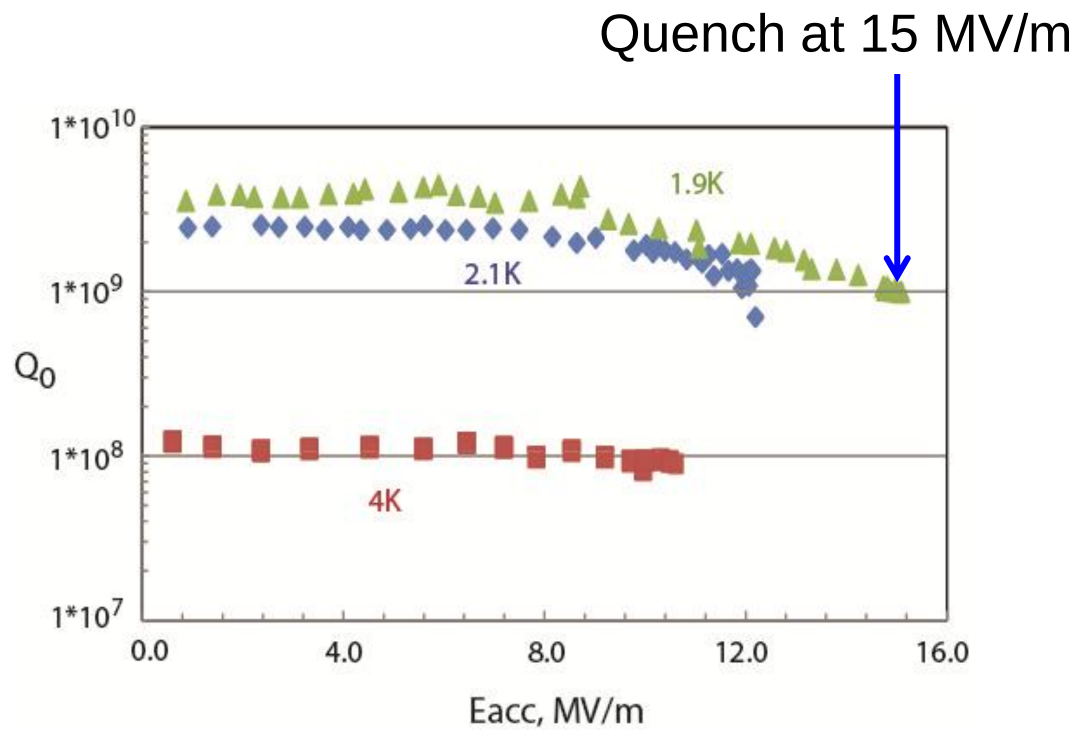
Higher $f \Rightarrow$ lower bunch charge + smaller footprint

Fabricated and BCP'ed at Niowave, then assembled and tested at LANL



2.1 GHz cavity test result



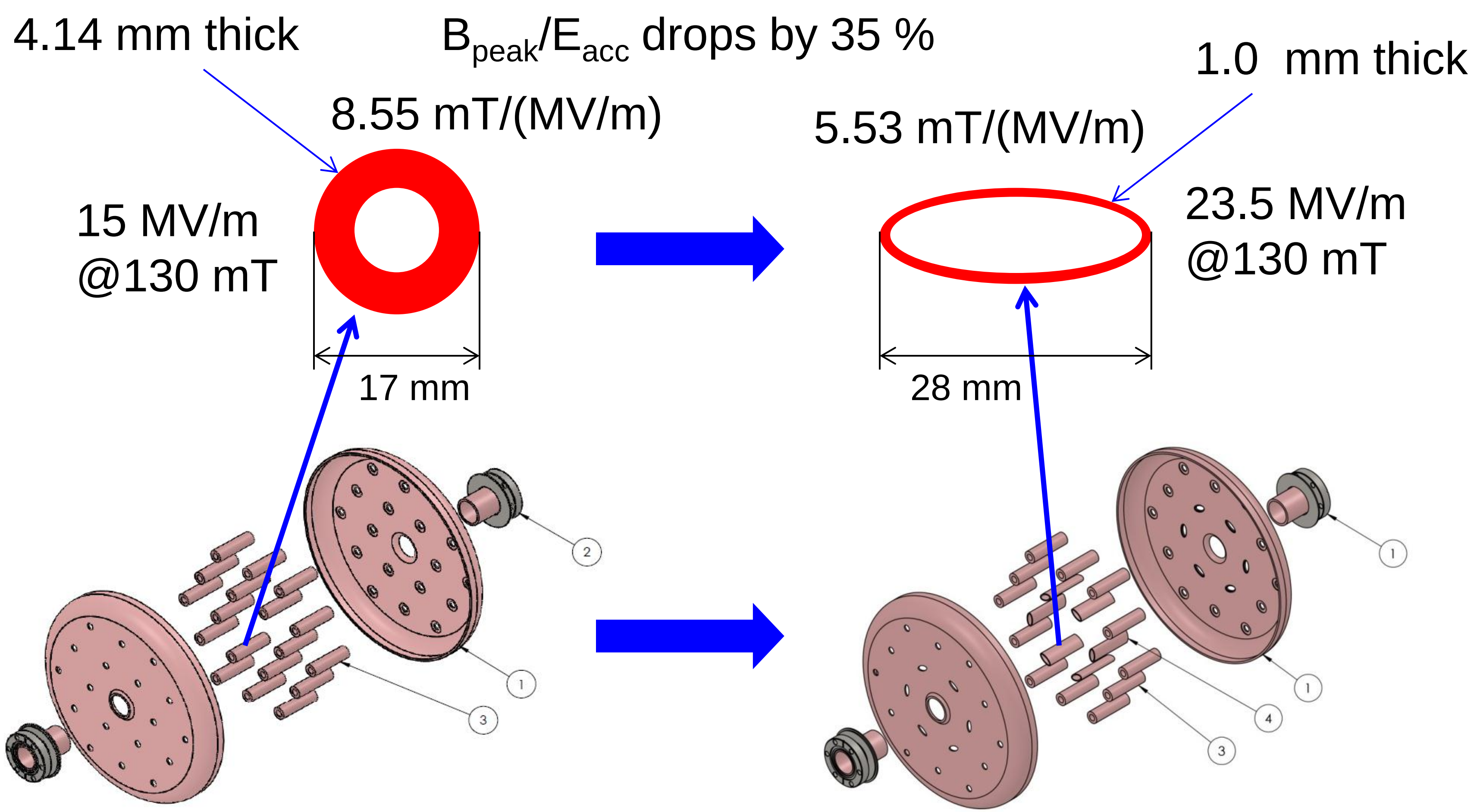


E_{peak}/E_{acc} = 2.22
B_{peak}/E_{acc} = 8.55 mT/(MV/m)

Max. B_{peak} ~ 130 mT

PRL 109 (2012) 164801

Plan to increase the accelerating gradient by changing the cross section of the first row pipes



Acknowledgements

- **LANL**
  - Mike Borden, Jim O'Hara and other AOT-MDE group members especially vacuum team members for their support and encouragement
  - Alan Shapiro (retired) and Mike Madrid (retired) for all their work at the SRF Lab.
  - Roland Schulze for AES/XPS analyses
  - Marilyn Hawley for AFM analyses
  - Nestor Haberkorn for magnetization measurements (currently with CNEA-Centro Atómico Bariloche, Argentina)
  - Yingying Zhang and Quanxi Jia for Polymer Assisted Deposition (PAD) studies on NbN and MoN. Dr. Zhang is currently with Tsinghua University, Beijing, China.
  - Leonardo Civale for leading the magnetization measurements and many useful discussions
  - Dave Devlin for setting up the MgB_2 costing system and other coating tests
  - Alberto Canabal (now with TriQuint Semiconductor) and Grigory Eremeev (now with JLAB) for testing samples at SLAC and cavities at LANL
  - Alp Findikoglu for measuring R_s of MgB_2 samples using parallel plate technique.

Acknowledgements (cont.)

- **ANL**
  - Mike Pellin and Thomas Proslier for ALD coating of alumina and other studies on dielectric materials
- **SLAC**
  - Sami Tantawi, Jiquan Quo (now at JLAB), Valery Dolgashev, Dave Martin and Charlie Yoneda for preparation and testing samples
- **Jlab**
  - Binping Xiao for measuring RF surface impedance of MgB_2 samples using their 7.5 GHz SIC system. Also, Anne-Marie Valente-Feliciano for preparing ECR Nb films.
- **Cornell University**
  - Alexander Romanenko for conducting TE_{01} mode cavity measurements to evaluate R_s vs. H for MgB_2 samples. Dr. Romanenko is currently with FNAL.
  - Hasan Padamsee for useful discussions and encouragement.
- **Temple University**
  - Xiaoxing Xi and his group members for preparing MgB_2 samples with HPCVD.

Acknowledgements (cont.)

- **KEK, Tsukuba, Japan**
  - Akira Yamamoto, Kenji Ueno, Masashi Yamanaka and Seiya Yamaguchi for support while at Tajima was at KEK on leave from LANL. Hitoshi Inoue for hydroforming and fabricating copper cavities.
  - Shigeki Kato for coordination with a company in Japan for mechanical and chemical polishing of copper cavity
- **NIMS, Tsukuba, Japan**
  - Akiyoshi Matsumoto for coordination with Kagoshima U. for MgB_2 coating and other support.
  - Eiichiro Watanabe, Hirotaka Ohsato and Daiju Tsuya for ALD coating of alumina
  - Minoru Tachiki and Hideki Abe for various discussions while Tajima was at NIMS in 2000.
- **Kagoshima University, Japan**
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Acknowledgements (cont.)

- **University of Wollongong, Australia**
  - Yue Zhao for coating MgB_2 using PLD technique
- **Superconductor Technologies, Inc. (STI)**
  - Brian Moeckly and Chris Yung for coating MgB_2 using reactive co-evaporation technique. (Dr. Moeckly is currently not with STI.)
- **Institute for Super Materials, ULVAC, Japan**
  - Tomohiro Nagata for SIMS analysis for CED Nb films and useful discussions (Dr. Nagata is currently with KEK on leave from ULVAC)
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  - Mahadevan Krishnan and Colt James for coating copper cavities with CED technique
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  - DOE/NP 2010 – present
  - DTRA 2008-2010